Cost Benefits of Weather Information for Winter Road Maintenance

Final Report
April 2009

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16. Abstract

This purpose of this research project is to provide a current benefit-cost assessment for weather information in winter road maintenance. To this end, the research team first summarized the weather information resources used by transportation agency personnel in making winter maintenance decisions and investigated how weather information was used to support winter maintenance operations, through extensive literature reviews and surveys to winter maintenance professionals and the meteorological community. Following this, the research team developed a model for winter maintenance costs. A methodology of artificial neural network and sensitivity analysis was proposed and applied to three case studies to analyze the benefits and costs associated with the use of weather information. The benefit-cost analyses showed that the use of weather information could bring more benefits than costs. Moreover, it was found that winter maintenance costs could be reduced by improving the accuracy of weather information and/or increasing the use of weather information. Finally, this study identified secondary benefits of deploying and using road weather information systems. These research results should help transportation agencies to guide and direct future investment in weather information services and technologies.

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COST BENEFITS OF WEATHER INFORMATION FOR WINTER ROAD MAINTENANCE

Final Report
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EXECUTIVE SUMMARY

This purpose of this research project is to provide a current benefit-cost assessment for weather information in winter maintenance. To achieve this goal, the research team first summarized the weather information resources used by transportation agency personnel in making winter maintenance decisions and investigated how weather information was used to support winter maintenance operations, through extensive literature reviews and surveys to winter maintenance professionals and the meteorological community. Following this, the research team developed a model for winter maintenance costs. A methodology consisting of artificial neural network and sensitivity analysis was proposed and applied to three case studies to analyze the benefits and costs associated with the use of weather information. Finally, this study identified secondary benefits of deploying and using road weather information systems. These research results should help transportation agencies to guide and direct future investment in weather information services and technologies.

The findings and conclusions of this research project are summarized as follows:

1) The survey of winter maintenance personnel found that free weather information sources, private-sector weather providers, and Road Weather Information System (RWIS) were the most widely used weather information sources. The other two sources, the road weather observation mesonets and Decision Support Systems (DSS), had fewer users; they usually collect road and weather data from two or more other sources such as the National Weather Service (NWS) and RWIS, and fuse them to generate information of interest for winter maintenance. Private-sector weather providers, who act similarly to mesonets and DSS, collect weather data from NWS or other sources to provide specialized information of current weather conditions and/or forecasts. Thus, free weather information sources and RWIS are the two primary direct sources for collecting road weather information.

2) Cost considerations and easy access contribute to the wide use of free weather information sources. However, these sources may have problems with timeliness and a lack of detail, which may result in the use of inaccurate weather information. Based on the survey of winter maintenance professionals, the accuracy of weather sources is the biggest barrier preventing the use of weather information.

3) One barrier to using private services and RWIS is the cost. For RWIS, the design and installation as well as communications are the highest cost components. Design and installation are one-time costs, however, and ongoing costs are perceived to be much smaller. The majority of the post-installation costs are related to maintenance. Survey responses indicated that the percentage of winter maintenance budgets spent on obtaining weather information is relatively low (less than 1 percent or between 1 and 5 percent).

4) Air temperature, wind, and the type and amount of precipitation are primary parameters of current and forecast weather conditions. Road weather elements such as pavement temperature, bridge temperature, and pavement conditions are also widely used in

winter maintenance. In addition to these, winter maintenance personnel are highly concerned with forecasts of the onset, conclusion, intensity, and duration of storm events. The importance of weather forecasts decreases with the scale of time from nowcasts to short-term, medium-term, and long-term forecasts.

5) The most noticeable benefit of using weather information for winter maintenance is reducing maintenance cost. The perception that using weather information could save on staffing, materials/chemicals and equipment costs was more likely to be reported by maintenance managers than by field crews/supervisors.

6) Survey results revealed that plowing, deicing, and anti-icing were widely used by survey respondents, and that the employment of anti-icing in winter maintenance is anticipated to increase. Weather information is important in supporting a variety of winter maintenance operations; however, respondents reported needing more weather information to support anti-icing and plowing/de-icing than to support sanding/grit operations. Together, these findings suggest that the demand for weather information among winter maintenance personnel will increase in the future.

7) Survey results showed that maintenance personnel relied less on forecast weather parameters than information on current conditions. Current road and weather parameters of interest included pavement temperature, air temperature, pavement surface condition, precipitation rate, precipitation occurrence, wind speed and direction, and humidity/dew point. Forecast road and weather parameters of interest included the onset/end time of precipitation, precipitation type and amount, pavement temperature trends, and pavement surface condition.

8) The use of weather information varied among the three case study states. The average frequency values of using RWIS and private weather forecasts were 2.75 (Iowa), 3.49 (Nevada), and 1.77 (Michigan). The differences among the states might have been due to their levels of trust in weather information services (e.g., accuracy) and associated service costs.

9) Compared with frequency, the average accuracies of weather information among the states had smaller variations, ranging from 3.4 to 3.6. (Accuracy takes the values of 1 to 5. A value of 3 means that the accuracy of fee-based weather information services is the same as a free weather service; the higher the value, the better.) The survey results indicated that fee-based weather information was more accurate than free weather services, especially for the Iowa and Nevada cases.

10) The case studies found that weather information use had positive effects on winter maintenance costs. Case studies collectively showed that winter maintenance costs decreased as the use of weather information increased or its accuracy improved.

11) It was found that accuracy had a greater effect on maintenance costs than frequency. In other words, winter maintenance costs were more sensitive to weather information

accuracy than to the frequency of its use. Hence, the improvement of weather information accuracy is critical to achieving more savings in winter maintenance.

12) The benefit–cost analyses showed that the use of weather information could bring more benefits than costs. The benefits and costs associated with weather information are summarized in the following table. The Michigan case had the highest benefit–cost ratio due to low costs in weather service. However, the percentages of benefits over total winter maintenance costs were 5.6 percent (Iowa), 6.5 percent (Nevada), and 0.9 percent (Michigan). Although the Michigan case had the highest benefit–cost ratio, the percentage of benefits over total winter maintenance costs is the lowest. For this reason, benefit–cost numbers in this research study cannot tell the whole story. Actually, the benefit–cost ratios of the Iowa and Nevada cases are more representative numbers because the costs associated with weather information in these two states were based on statewide numbers, while the Michigan case was not. Please note that the amortized RWIS capital costs were excluded when calculating the cost of weather information for winter maintenance, considering that such costs are often covered by construction projects and the benefits of RWIS are well beyond the winter maintenance community. The in-house equipment and personnel costs related to RWIS maintenance were also excluded since they are often considered to be part of other ITS (intelligent transportation systems) and/or operations costs and hard to track down. The cost of maintaining RWIS sensors, however, were included as part of the maintenance contract. For some agencies, it may be deemed necessary to include some of the abovementioned costs in the total cost of weather information for winter maintenance.

Summary of Benefit–Cost Analysis

Case Study State	Winter Season	Winter maintenance Cost ($ 000s)	Benefits ($ 000s)	Weather Information Costs ($ 000s)	Benefit-Cost Ratio	Benefits/ Maintenance Costs (%)
Iowa	2006–07	14,634	814	448	1.8	5.6
Nevada	2006–07	8,924	576	181	3.2	6.5
Michigan	2007–08	31,530	272	7.4	36.7	0.9

13) The benefit–cost analysis only considered agency benefits and did not include benefits to motorists and society. The case studies show that the use of weather information is able to reduce resource usage, which in turn can reduce degradation of the surrounding environment, corrosion effects on motor vehicles, and infrastructure damage. In addition, it will benefit motorists with reduced delay and improved safety as the road surface returns to a normal condition more quickly.

14) Weather information from RWIS is mainly used by maintenance personnel, but it can be also useful to other users. The study identified potential RWIS extensions as well as associated benefits and costs. RWIS has been widely used in many applications such as weather-responsive operations, dynamic warning systems, anti-icing spraying systems,

and traveler information systems. Information provided by RWIS can improve accessibility of information, reduce vehicle crashes and crash severity, help travelers develop better trip planning, provide more comfortable driving and so on.

The research team also provided recommendations for the use of weather information in winter maintenance. The recommendations of this study are as follows:

1) A variety of weather sources can provide useful weather information for winter maintenance. It is recommended that a state DOT identify the resources that can be used within the state. A comparison of the sources (e.g., accuracy, ease of access, cost) may be conducted to rank the sources and provide recommendations.

2) Use of accurate weather information in winter maintenance is critical to reducing costs. The accuracy of weather information, however, is usually limited by the availability of weather sources, budget, and weather detection and forecasting technologies. Thus, it is recommended that state DOTs use the most accurate weather sources for winter maintenance within budget limits and other constraints.

3) The level of trust in weather information and the frequency of using weather information are interrelated. Increased level of trust will improve the use of weather information and, as a result, save more in winter maintenance. For this reason, it is important to know about the level of trust among winter maintenance personnel towards various weather resources. If accuracy problems exist with fee-based services, provide feedback to service providers to solve problems or find better alternatives.

4) It is also recommended that the use of weather information be more focused towards the road environment. The use of road weather information (e.g., pavement temperature and trend, bridge temperature) is important information for developing better maintenance strategies.

5) The case studies collectively showed that winter maintenance costs decreased with the increase use of weather information or accuracy. As such, the maintenance agencies should continue to invest in road weather information with high accuracy (such as RWIS and customized weather service) and to ensure high usage of the existing road weather information services. One way to boost the user acceptance and to increase the usage of weather information would be through training along with close communication of weather service providers and winter maintenance practitioners. It is also recommended that agencies leverage existing infrastructure (e.g. existing ITS sites with available power and communications) when choosing RWIS installation sites to help reduce costs.

CHAPTER 1. INTRODUCTION

In the northern United States and Canada, snow and ice control operations are essential to ensure the safety, mobility and productivity of winter highways, where the driving conditions are often worsened by the inclement weather. The U.S. spends $2.3 billion annually to keep roads clear of snow and ice (1); in Canada, more than $1 billion is spent annually on winter maintenance including road salts (2). Transportation agencies are under increasing pressure to maintain high levels of safety and mobility even during the winter months, while working with limited financial and staffing resources and recognizing the environmental challenges related to chemical and material usage (3, 4, 5).

One key component of helping to meet these challenges is obtaining and using accurate weather information. The benefits of accurate weather information are clearly evident when contrasted with some of the costs of inaccurate weather information, such as excessive use of chemicals and materials, failure to respond in a timely matter to a storm event (resulting in greater crash risk and user delay), unplanned use of overtime staffing, and others. Improvements in weather information can help in all stages of winter storm response, including pre-, during and post-storm.

Weather information can be divided into two temporal categories: observations, which reflect current conditions; and forecasts, which predict future conditions (6). While understanding current conditions can be valuable, predictive forecasts can be used to develop an appropriate response to the weather. Forecasts may be subdivided into decision scales: micro (less than 1 hour); meso (1-6 hours); synoptic (6 hrs-week) and climatic (weeks and beyond) (7). These scales correspond to the different ways that a forecast may affect future activities. A micro-scale analysis may be useful in deciding an application rate, while a synoptic-scale would be helpful for staffing and resource planning.

Weather information may be gathered from a variety of sources. One trend among transportation agencies is to use sources that provide information more customized toward the roadway environment. This includes development of forecasts at a smaller geographic scale, in addition to focusing on weather at the road surface, where reduced pavement friction can adversely affect motorist safety and travel time. A variety of innovations for weather information have emerged in the last couple of decades, many of which are discussed in Chapter 2. With the wide array of sources available, it is important for a transportation agency to identify the benefit-cost tradeoff associated with incremental investments in improved weather information.

The Strategic Highway Research Program (SHRP) conducted research regarding the potential benefits of improved weather information (6, 8) in the early 1990s. This research provided a comprehensive examination of road weather information systems (RWIS) at a time when RWIS implementation in the United States was not widespread. The report dealt with a variety of RWIS issues ranging from sensor accuracy to maintenance, from communications to institutional issues. The research report also included a section analyzing the potential cost-effectiveness of adopting improved weather information (including RWIS and tailored forecasting services), which used a simulation model based on data from three U.S. cities.

Today's winter maintenance context differs from the context in which the earlier SHRP research was conducted. Many assumptions are no longer valid, different technologies and tools are available, and different practices and procedures are in common use. It is important to re-visit this benefit-cost assessment, from the perspective of the weather information sources that are in use today, the treatment practices that are used, and the tools that are available.

In its mission statement, the Aurora Program exists to foster "collaborative research, development and deployment in the field of road and RWIS, serving the interests and needs of public agencies." (9) In light of the complex challenges in winter maintenance activities today, public agencies have a compelling need to identify the best types of weather information sources for maximizing benefit to the agency and the traveling public.

The purpose of this research project is to provide a current benefit-cost assessment for weather information in winter maintenance. This assessment will update and build upon the work completed in the earlier SHRP project (6, 8). To achieve this goal, the research team's approach synthesized information gathered from the existing literature (CHAPTER 2), survey responses from transportation agencies involved with winter maintenance (CHAPTER 3 and CHAPTER 5), and outreach to the meteorological community (CHAPTER 4). In addition, the research team proposed using a detailed case study approach to evaluate the benefits and costs of weather information for winter maintenance (CHAPTER 6). CHAPTER 7 presents the secondary benefits of RWIS. Finally, CHAPTER 8 summarizes the conclusions of this research study and provides recommendations for using weather information in winter maintenance. The results of this research are useful to help transportation agencies to guide and direct future investment in weather information services and technologies.

CHAPTER 2. WEATHER RESOURCES

Due to the broad effects of weather on the roadway system, a variety of initiatives/activities have been proposed and carried out to improve the performance of the transportation system during inclement weather. Examples of these initiatives/activities are as follows:

- During 1988-1993, the SHRP began the process of investigating weather technologies with nearly $20 million being spent in a maintenance operations research program. This program initiated today's usage of RWIS in North America. Later in 1996, the Aurora pooled fund program was founded. The bulk of RWIS research is conducted through this program that brings a number of U.S., Canadian, and European agencies together.
- In 2000, the Federal Highway Administration (FHWA) developed the Surface Transportation Weather Decision Support Requirements (STWDSR) through collaboration with state Departments of Transportation (DOTs) and national labs (10, 11). In addition to documenting the specific weather information needs of various transportation professionals during different time frames, this project provided the framework to integrate this information. The first example of this integration was a prototype winter Maintenance Decision Support System (MDSS).
- In 2002, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) worked with transportation stakeholders and developed the *Weather Information for Surface Transportation National Needs Assessment Report* (12). This effort has been followed up by subsequent reports including *First Steps to Improve the Nation's WIST Capabilities and Services* (13) and *Update on Weather Impacts and WIST Results* (14).
- The American Meteorological Society (AMS) formed an Ad Hoc Committee on Surface Transportation in the mid-1990s. In 2003, the AMS held a forum to address various issues connected with effective use of road weather information. Event discussions were summarized in a report, *Weather and Highways*, published in 2004 (15).
- The AMS created a Standing Committee on Intelligent Transportation Systems (ITS) and Surface Transportation Weather in 2002. This standing committee has worked together with ITS America's Weather Information Applications Special Interest Group (WIASIG) to better integrate the meteorology and ITS communities. The groups have worked together to support integration of weather information into 511 traveler information, ITS architecture and standards development, MDSS and other initiatives (16).
- In 2004, the National Research Council (NRC) completed a study and published a report titled *Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services* (17), which presents a research agenda for improving road weather services.
- In 2005, the Federal Highway Administration's Office of Transportation Operations and the ITS Joint Program Office (JPO) created the concept for a nationwide surface transportation weather observing system. Rather than imposing another difficult project acronym on the community, the term *Clarus* (which means "clear" in Latin) was selected (18).

The growing interest in weather information implies that such information could have significant value in helping to meet the challenges of adverse weather on the roadway system. The value of this information depends, however, on the type of weather information received, and the surface transportation application toward which it is directed.

The purpose of this chapter is to summarize the weather information resources used by transportation agency personnel in making winter maintenance decisions. This chapter summarizes some of the principal weather information sources which are available to (and used by) transportation personnel to support winter maintenance operations. Information on these sources was gathered through a literature review. A comprehensive reference list was collected from a variety of sources including (but not limited to) the Transportation Research Information Service (TRIS), the FHWA web site, and Google scholar. These references were reviewed to provide a thorough picture of various weather information sources for winter maintenance. The introduction to each source, the extent of its utilization, and its applicability to winter maintenance are described as follows.

2.1 National Weather Service

The National Weather Service (NWS) is an agency within the U.S. Department of Commerce's National Oceanic and Atmospheric Administration. According to its mission statement, the purpose of the NWS is to provide "weather, hydrologic, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy." Since the NWS is a government agency, most of its products are available free of charge.

2.1.1 Weather Observations

The NWS provides current observations for local areas within each state. Each state has one or more NWS offices which provide forecasts for the state. Current weather conditions are available online and updated once per hour. The observations include wind speed and direction, visibility, sky conditions, temperature, dew point, relative humidity, pressure, and pressure tendency. In addition, it provides a summary of the past 24-hour weather conditions.

Through the deployment of Next Generation Weather Radar (NEXRAD) in the 1990s (19), the NWS provides continuous radar data to monitor precipitation (onset time and duration), severe weather complexes, and indicate wind speed and direction when operating in clear air mode (17). Thus, the NEXRAD can be a useful tool for roadway maintenance decision makers. A primary surface-weather-observing system in the U.S. is the Automated Surface Observing System (ASOS). ASOS is a joint program of the NWS, the Federal Aviation Administration, and the Department of Defense. As of 2006, there are nearly 1,000 ASOS sites across the U.S., of which 569 FAA-sponsored and 313 NWS-sponsored (15). ASOS sties are located at airports throughout the country. The sensors that comprise ASOS detect weather conditions and are able to update official weather observations up to 12 times per hour. ASOS's constant stream of data helps the NWS increase the accuracy and timeliness of its forecasts and warnings. ASOS is a fully automated system that provides meteorological observations without human observers. ASOS detects significant changes, transmitting hourly and special observations via the various networks such as FAA ground-to-air radio and telephone dial-in port. The basic weather elements provided

by ASOS include sky conditions (clouds up to 12,000 feet), surface visibility, present weather (type and intensity for rain, snow, and freezing rain), surface pressure, air and dew point temperature, wind (direction, speed, and character), precipitation accumulation, and selected significant remarks (e.g., pressure change tendency, wind shift, beginning/ending times of precipitation) (20).

ASOS is valuable to many users. ASOS is designed to support NWS warning and forecast operations, the FAA aviation weather needs, and hydrological and climatological programs. While the observations from the ASOS are representative of a small area near the site, but are not necessarily convenient or applicable to the roadway environment.

Another aviation weather system is the Automated Weather Observing System (AWOS). AWOS is designed to gather and disseminate weather data primarily to assist the aviation community. AWOS receives input from multiple sensors. Five standard groups of sensors are defined to provide different weather elements. Additional sensors can be added to any AWOS configuration. The most highly configured AWOS detects and outputs weather information including wind, temperature, dew point, density, visibility, precipitation, sky condition, present weather and lightening, and freezing rain (21). Currently there are over 600 AWOS sites in the U.S. Like ASOS, AWOS is not designed to observe road weather information.

2.1.2 Weather Forecasts

Numerical weather prediction models have steadily improved since 1960s. At the end of 20th century, prediction models had excellent performance with the average error less than 20 percent. The highest-resolution NWS models are run on horizontal grids on the order of 10 km and are able to capture extratropical cyclones and the smoother characteristics of associated fronts. However, they still are not able to capture phenomena such as the scale of individual thunderstorms or localized wind events, which are critical to surface transportation. Moreover, the amount of available data, especially near surface, is limited. (17)

The NWS offers weather forecast services using numerical weather prediction. The NWS currently is running the Eta (now known as NAM) model on a 12-km horizontal grid out to 3.5 days, 4 times per day (22). Forecast services can be produced from statewide area to site-specific locations such as airports. Model Output Statistics (MOS) have been a useful tool for forecasters for years and have shown improving forecast performance over time. MOS is a statistical post-processing scheme applied to the output of a numerical weather prediction model (23). These MOS forecasts predict weather elements that can be categorical or continuous data. For example, continuous data include, but are not limited to air temperature, dew point temperature, wind direction, and wind speed (23).

The National Digital Forecast Database (NDFD) is the foundation of the NWS digital service program. The NDFD consists of gridded forecasts of weather elements. Anyone will be able to use Internet access to download information from the NDFD including official NWS forecasts. The database will be made available to all public and private sector users and will allow them to create their own text, graphic and image products. Also, private companies will be able to use the official NWS forecasts instead of relying on direct model output or post-processed products (e.g., MOS) because forecast information is in digital form and available from a single source (24).

2.2 Free Private-Sector Sources

Several types of private-sector media sources such as newspapers, local television and radio, network or cable television and the Internet, are able to provide weather information to the public at no charge. The detailed descriptions and discussion of such weather sources are provided in the SHRP report (6). Hence, the features of these media for weather information are only briefly summarized in this report. Generally, weather information provided by media outlets is for large areas, and defines average conditions or a range of conditions and has the problems of timeliness and lack of detail. However, it may be used as additional weather information for roadway maintenance.

2.2.1 Newspapers

Local newspapers publish forecasts for specific cities or sub-regions. In some cases, these forecasts are developed by in-house staff, but are more often received as a subscription from a private-sector meteorological service (see Section 2.3). Although newspapers often provide detailed information on weather events at different regional levels, there is a time lag between the observation of weather information and the printing of that information. Forecasts provided by newspapers are usually up to 12 hours old by the time they are read. Also, they can provide little more than expected general information in an area.

2.2.2 Local Radio and Television

Local radio and television stations provide similar forecast information as newspapers, but will typically have improved timeliness. In addition, in some rural areas, the radio station may provide more locally specific coverage than the closest newspaper. Nonetheless, broadcast frequency remains relatively infrequent. Consequently, they are not very applicable for gathering weather information for winter maintenance.

2.2.3 National Broadcast or Cable Television

In addition to local broadcasts, there are national network and cable broadcasts of weather conditions and forecasts (e.g. The Weather Channel). The broadcast media have an advantage over newspapers in providing more timely weather information. The Weather Channel, for example, provides the latest National Weather Service (NWS) forecasts for local areas many times each hour. Overview of national weather patterns, radar and satellite imagery, and highlights areas of severe weather are provided by the channel. Weather information is central to this channel's purpose; therefore, there will likely be a relatively short lag time regarding learning about current conditions, as well as changes in forecasts. Several other national broadcast outlets such as ABC, CNN, CBS, FOX and NBC also provide such services.

In general, forecasts provided by these services are presented from a national perspective, and therefore do not provide great detail about local road and weather conditions. However, there are a large number of local cable news/weather channels which do provide localized weather information for their market areas.

2.2.4 Internet Weather Providers

Many companies provide free weather information via the Internet. These services provide hourly current weather information (e.g., temperature, humidity, wind), up to 5 day weather forecasts of temperature and precipitation) as well as NEXRAD radar and satellite imagery. Examples of these providers include WeatherBug (http://www.weatherbug.com), provided by Automated Weather Source; AccuWeather (http://www.accuweather.com); Intellicast (http://www.intellicast.com) and Weather Underground (http://www.wunderground.com). These companies earn revenue through advertising on their web sites. They also may earn revenue through providing customized forecast services; these are described further in Section 2.3.

2.3 Private-sector Weather Providers

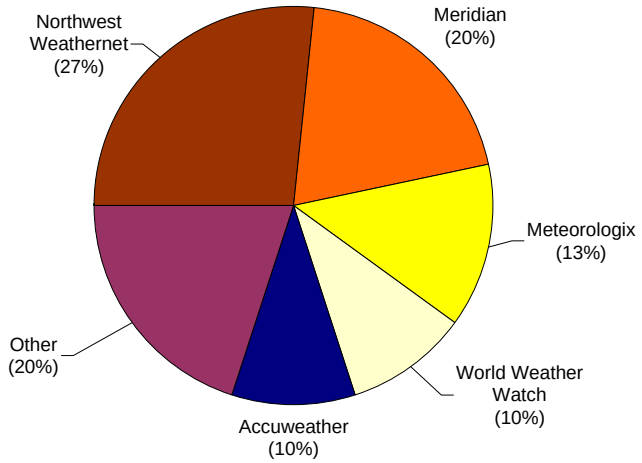
Private-sector weather information providers refer to for-fee services by which the private sector provides customized weather information (typically forecasts) to an agency. Private-sector weather providers are sometimes referred to as value-added meteorological services (VAMS), private weather services, or private meteorological services. It refers to commercial meteorological businesses services that take information from the NWS or other sources and use sophisticated weather models that ingest weather information to generate specialized information and enhance levels of forecast quality for their clients.

VAMS provide forecasts in various ways (6). Some of them only provide weather data to subscribers, and some provide forecasting services. They may offer forecasting information year-around, seasonally, or on an as-needed basis. For forecasting services, VAMS can provide weather forecasts, and road weather forecasts. For example, the Meridian Environmental Technology, Inc. developed the Advanced Transportation Weather Information System (ATWIS) to provide decision support in planning and managing road construction and maintenance activities (25). The system provides services including: 1) site-specific weather and road forecast information for selected highways; 2) 36- to 48-hour area-specific forecasts; 3) current and forecast road restriction recommendations based on freezing and thawing indexes combined with soil moisture data; and 4) a five-day site-specific, hour-by-hour weather forecast. VAMS also provide services to the public such as the 511 system designated by the Federal Communications Commission, which drivers can call free to learn about current and forecast road and weather conditions on the roadway.

Private-sector weather providers work with a customer to tailor forecasts that better meet their needs. Enhanced geographic and temporal details are key advantages of using these providers, while cost is often the barrier for transportation agencies.

An online survey on the Snow and Ice List Serve (26) was conducted with respondents from 19 U.S. states and 4 Canadian provinces (27). All respondents indicated that they paid for customized weather forecasts to assist winter road maintenance activities. The most commonly cited private-sector weather providers were Northwest WeatherNet, Meridian, Meteorlogix, World WeatherWatch, and AccuWeather as shown in Figure 1. Northwest WeatherNet was the primary provider of road weather forecasts.

Several meteorologists affiliated with private-sector weather forecasting services were interviewed for this project; more information about their perspectives on these services is in CHAPTER 4.



(Source: 27)

Figure 1: Most Commonly Used Weather Service Providers

2.4 Public-sector Custom Forecasting Services

Starting with the 2002 Winter Olympics, the Utah Department of Transportation (UDOT) has invested in improving its weather forecasting services through a separate and unique Weather Operations Program within the state's Traffic Operations Center (TOC). Meteorologists are physically housed within the TOC, which facilitates integration of weather information into many UDOT operations. Quality control of weather forecasts is ensured with the staffed meteorologists. Weather briefings are conducted in the TOC on a daily basis, involving TOC personnel, area supervisors, and maintenance foremen. In addition, the program provides tailored crew-specific forecasts in a text format for all 82 maintenance sheds (28).

The program provides various services to numerous customers within UDOT. It provides the office of central maintenance with year-round, long-term weather forecasts that are mainly used for planning in terms of materials (storage and purchasing), staffing, and equipment. It provides construction engineers and contractors with weather forecasts for highway construction and rehabilitation projects, which are mainly used to plan for staffing, materials, and equipment. The program provides pre-storm, during storm and post-storm weather forecasts to the maintenance engineers, area supervisors and local sheds. In addition to snow and ice control, such forecasts are also useful for the operations/projects of road rehabilitation, weed abatement, and avalanche safety. A recent evaluation showed this approach to have a benefit-cost ratio of 11:1, which may lead other transportation agencies to consider similar approaches (29).

2.5 RWIS

Over the last couple of decades, state highway agencies have been exploring new ways to improve roadway safety during inclement weather and to use labor, equipment, and materials as cost-effectively as possible. Research into pavement sensors found that weather information technologies can help attain these purposes. Starting in the 1990s, several countries in Europe have deployed weather information gathering systems nationwide to assist snow and ice control managers to make decisions. A scanning tour of these systems in the mid-1990s led to the deployment of similar systems in North America, called road weather information systems, or RWIS[1].

RWIS refers to an aggregation of roadside sensing and processing equipment used to measure current weather conditions at the road environment, and transmit the information. Weather data are collected by sensors placed at the roadside or in the roadway. The most visible components of RWIS are the roadside installations like those shown in Figure 2. Remote Processing Units (RPU) placed along the roadway may contain some or all of the road and weather sensors. A typical RPU consists of "atmospheric sensors mounted on the tower, sensors embedded in the pavement surface and beneath the surface, and an enclosure which contains data processing capability and Communication Processing Unit (CPU) where they may be stored, retransmitted to other workstations or locations, or accessed directly. The CPU can be a separate computer or a workstation. Another component of RWIS is the data processing and display capability used by the maintenance personnel. The actual system configuration depends on the management structure of the maintenance organization." (8).

Figure 2: Example Environmental Sensor Station Deployment[2]

[1] Iowa DOT has deployed RWIS for snow and ice control since 1988.

[2] Some ESS utilize video cameras for relaying visual information about weather and road conditions such as fog, rain, and snow.

Environmental sensing stations (ESS) are components of RWIS that provide environmental data. ESS installation may be characterized as either regional or local. Regional sites focus on defining initial conditions to support road weather prediction models, providing ground truth measurements for evaluating forecast accuracy, and improving the ability to anticipate weather changes. They are generally sited to be representative of conditions in the area, and thus are recommended for placement in areas of uniform roadway conditions in flat, open terrain. Local sites require sensors to be placed to measure whatever conditions are of most interest for road weather at specific points, such as icy pavement, low visibility, and high winds (30). As of 2006, there are over 2,400 ESS in 49 states and the District of Columbia (31).

RWIS-ESS differ from conventional weather stations in that they are deployed in the immediate highway environment, they often measure conditions on the roadway itself; and they are generally deployed where roadway weather conditions tend to be worst. In addition to collecting atmospheric data (e.g., air temperature, humidity, wind), RWIS also are able to detect roadway conditions (e.g., pavement temperature, pavement condition). Pavement sensors may be very useful in helping to forecast the likelihood and timing of icing events; however, due to their cost, not all RWIS-ESS will use these sensors (27).

The collected atmospheric and surface data are used directly by private-sector weather forecast providers to provide nowcasts and forecasts. Atmospheric data are used in assisting meteorologists to make detailed site-specific forecasts. Also, they are useful to understand the weather conditions on the roadway. Among those data, pavement temperature and sub-surface temperature are primary weather elements to determine if ice will form or snow will accumulate on the pavement (6). The two purposes of the deployment of RWIS by most states are to monitor current weather conditions at a specific location and to forecast weather conditions in advance (32). Although real-time weather information is important, the greatest benefits of RWIS are accrued through the use of tailored forecasts such as those aimed at supporting maintenance operations (31).

RWIS were first used by highway maintenance personnel to assist in the decision making process of applying labor, equipment, and material during the course of a storm event. Data gathered from RWIS is used for monitoring and planning operations such as scheduling personnel, selecting roadway control materials, and deploying equipment as cost-effectively as possible. With advances of technology in surface transportation, environmental data is now being disseminated to a wide range of transportation users and operators including (but not limited to) the traveling public, traffic managers, incident management teams, and emergency response personnel. Also, it is useful for roadside vegetation spraying and traffic lane striping operations. (31)

While RWIS provide detailed weather information, they do so only for specific points along the roadway; information on conditions between these points must be generated from other sources and/or interpolated. Moreover, there are significant costs associated with RWIS networks, not only for initial installation activities, but on-going maintenance, calibration, communications and power.

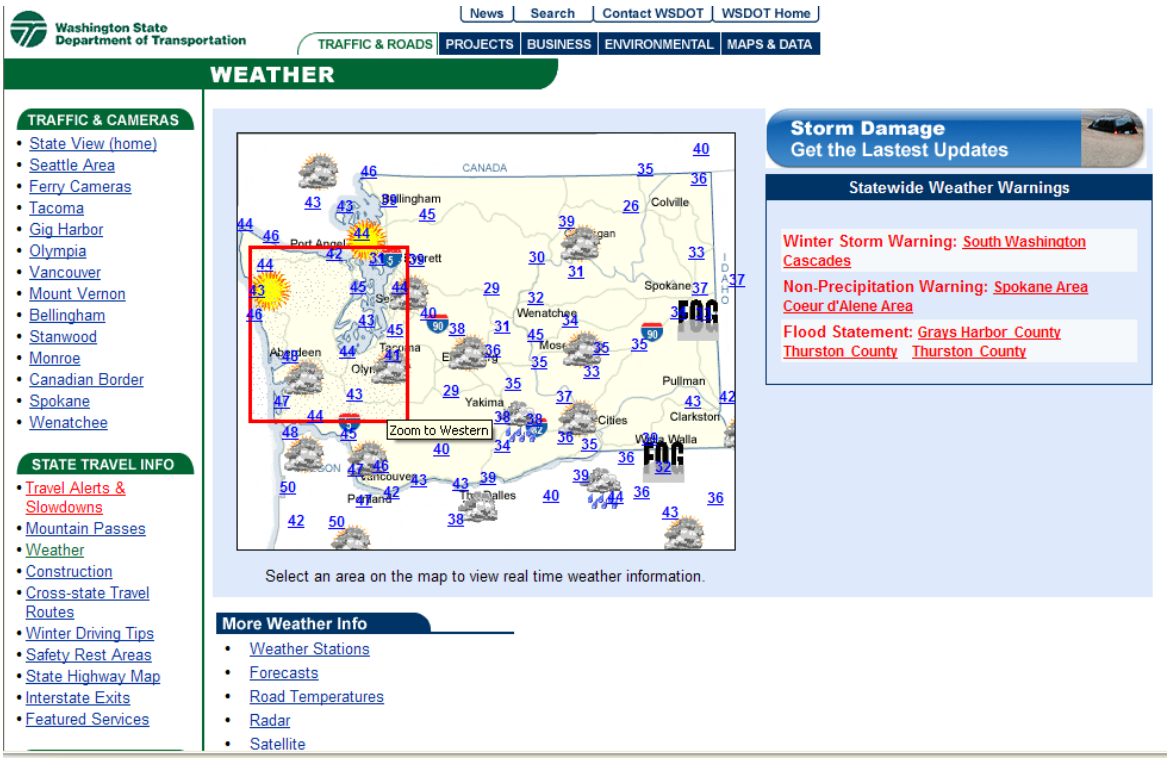
Despite the costs of deploying RWIS, research using a benefit/cost model indicated that the deployment of RWIS had a benefit/cost ratio of up to 5 (6). The deployment of RWIS has many benefits such as improvements in Level of Service (LOS) (e.g., safer travel), cost savings, better maintenance response strategies, improved environmental quality (e.g., less salt usage), indirect benefits (e.g., reduced accident rates), and other benefits (33).

2.6 Road Weather Observation Mesonets

An emerging approach for gathering weather information is to combine information from several sources to improve the density of observations, without the expense of mammoth investment in new RWIS sites. This is an approach using mesonets, which are defined as regional networks of observing stations with station spacing such that weather features on a mesoscale (i.e. a range of few miles) can be resolved (34). Several initiatives have sought to establish mesonets for road weather purposes. These mesonets seek to include transportation agency weather sites along with sites maintained by other agencies, such as resource and land management agencies. Examples of mesonets are described in this section.

2.6.1 rWeather

The Washington State Department of Transportation (WSDOT) and the University of Washington created and maintain rWeather, a web-based system to collect real-time and predictive statewide road and weather information and disseminate it to WSDOT maintenance and other decision makers, as well as to the public. rWeather integrates weather data from nearly 400 weather stations throughout the state and offers the data at a single location in a graphic format. The MM5 forecast model used for rWeather is generated by the Northwest Regional Weather Consortium and the University of Washington. In February 2004, the rWeather website became part of WSDOT's Statewide Traveler Information site (35).



(Source: 35)

Figure 3: A Snapshot of rWeather Interface

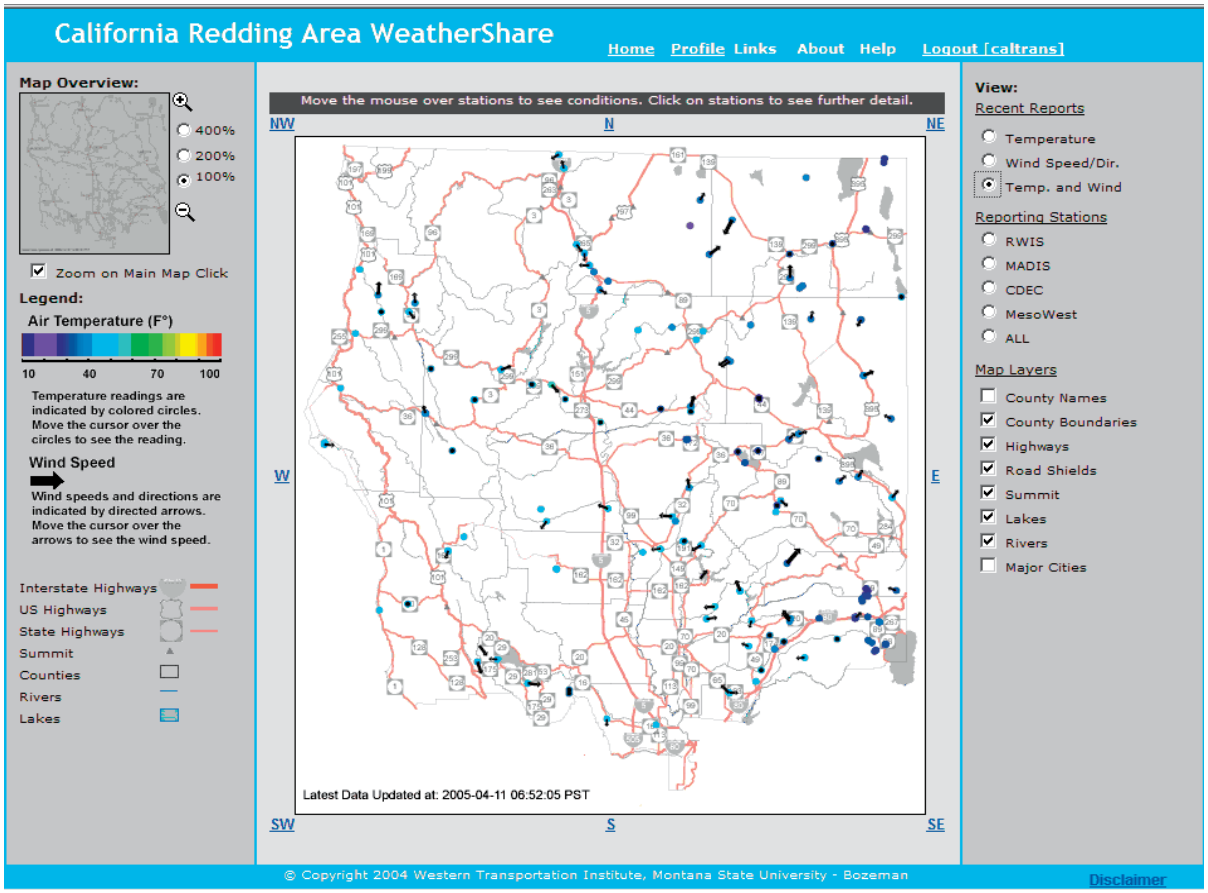
Figure 3 displays an interface of the rWeather service. By selecting a specific location on the map, users can view real-time weather information including surface temperature, air temperature, humidity, dew point, visibility, wind speed, and wind direction. Real-time information is updated every 20 minutes. The rWeather also displays 6-day weather forecasts adapted from the NWS.

A study was conducted to evaluate the impacts of rWeather on WSDOT winter road maintenance activities, in which questionnaires were distributed to area superintendents, supervisors, and lead technicians. A total of 129 questionnaires were returned and analyzed. Of the 79 percent of respondents who were aware of the rWeather website, 78 percent had used it. Nine of the ten features on the rWeather website were rated useful by at least half of the respondents. The most valuable features recognized by maintenance personnel users included: NWS warnings, satellite and radar images, and the statewide weather map. On the other hand, less than half of the respondents indicated that the rWeather pavement temperatures feature was useful. Approximately 70 percent of respondents wanted more investment in training related to interpreting weather data, and 50 percent of respondents wanted additional training to improve anti-icing strategies. The study recommended that comparisons be made between forecast and actual pavement temperatures and atmospheric weather conditions, and the findings shared with maintenance personnel (36).

2.6.2 WeatherShare

Similar to rWeather, California's WeatherShare is a web-based system that features the integration of regional weather and road data and forecasts from multiple sources and agencies. Phase I of WeatherShare focused on 11 counties in Caltrans District 2 as well as 9 counties in the adjacent Caltrans districts (37). The goal of WeatherShare is to streamline currently available weather and road data from California Department of Transportation (Caltrans) RWIS sites, NWS sites, and other sources available in the region into one single source easily accessible by incident responders and potentially the traveling public. The system allows users to view a compilation of all available road weather information from various sources in the region, increasing the efficiency of situation assessments for a variety of purposes, including incident management, highway maintenance, emergency medical services, traveler information, and, possibly, homeland security applications. WeatherShare does not offer interactive or customized weather forecasts. WeatherShare was funded by Caltrans and created by the Western Transportation Institute.

Phase II is under way to expand the Phase I product, a proof-of-concept system (38), to cover the entire state and to enhance its functionality and user interface. In addition, the research team will assist Caltrans in analyzing the business case while developing partnerships and plans for long-term maintenance and management of the system. The team will evaluate system use and functionality over multiple seasons and across a wide audience of prospective users with results incorporated in the business case analysis. In conjunction with evaluation, WTI will conduct an on-going needs and requirements analysis and, where appropriate, conduct development and outreach to address identified needs and requirements. A snapshot of the proof-of-concept WeatherShare interface is shown in Figure 4.



(Source: 38)

Figure 4: A Snapshot of the Proof-of-Concept WeatherShare Interface

2.6.3 WeatherView

In 1999, the Iowa Department of Transportation provided public access to weather information via the WeatherView online web site, describing both atmospheric and roadway conditions throughout sites in the state of Iowa. Two years later, a project was conducted to improve several existing components as well as developing new components (39).

Figure 5 shows a graphical user interface of WeatherView. WeatherView is maintained by the Iowa Department of Transportation to collect real-time and predictive statewide road and weather information and disseminate it to DOT maintenance and other decision makers, as well as to the public (40). The information is from a variety of sources, including RWIS sensors, AWOS systems located at 41 Iowa airports, regional forecasts provided for Iowa DOT by a private contractor, and contractor-generated bridge frost forecasts. The WeatherView is able to provide 2-day hourly weather forecasts for each county in the state.

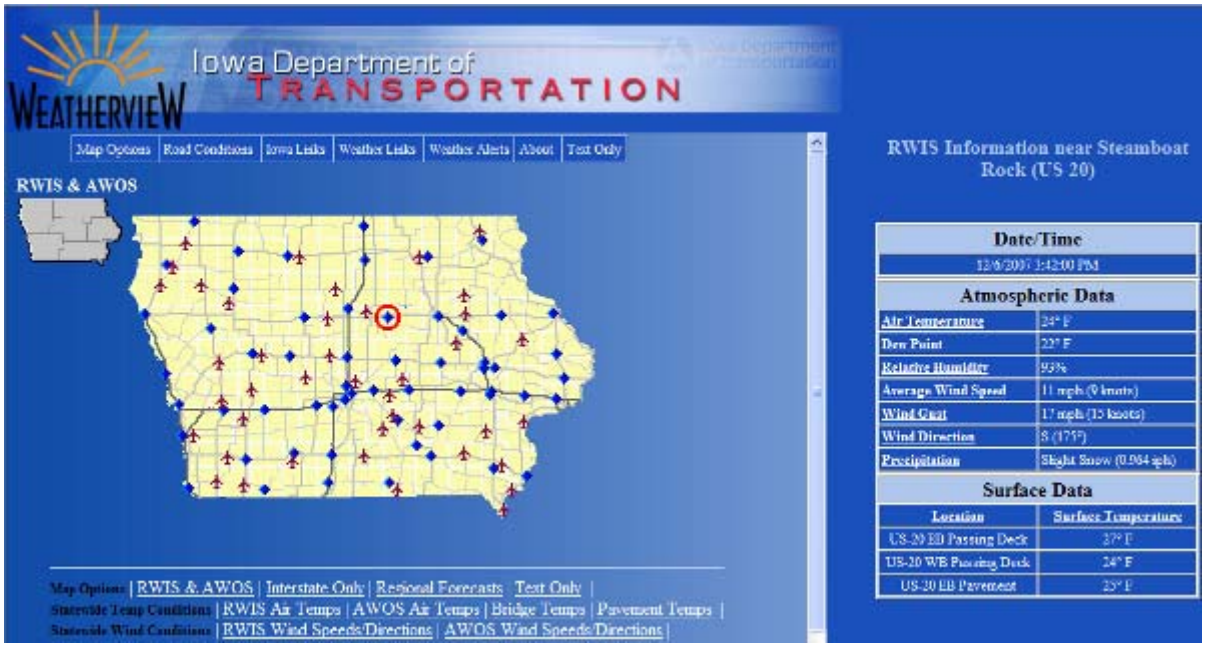


Figure 5: A Snapshot of the WeatherView Interface

2.6.4 Clarus

The *Clarus* Initiative is seeking to develop a national mesonet for road weather information. Under development and funded by the Federal Highway Administration, *Clarus*' goal is to "develop and demonstrate an integrated surface transportation weather observation data management system, and to establish a partnership to create a nationwide surface transportation weather observing and forecasting system" (18). Such a "system of systems" would "collect, quality control, archive, and disseminate surface transportation weather observations" (18). It is envisioned to improve surface transportation weather forecasting with enhanced data density, quality and integration. Three multi-state demonstrations are currently underway, and grants have been provided for states to integrate their RWIS data into *Clarus*.

2.7 Decision Support Systems

The preceding sections indicate the breadth of weather information sources which may be available to winter maintenance practitioners. The number of these sources, along with the diversity of current conditions and forecasts available through each source, make it challenging to readily understand the current weather environment, and to make appropriate tactical decisions. The default mode of operation has, in many cases, resembled what one document called "swivel-chair integration" (14), where a human is responsible for aggregating, assimilating and acting upon vast amounts of information in a short time window. An alternative approach is to harness improvements in information technology to fuse numerous data sources into a simpler interface that makes it easier to make more accurate and timely responses to winter storm events.

Decision support systems (DSS) are computer-based information systems including knowledge based systems that support decision-making activities. Several DSS have been developed in order to more effectively integrate information about current conditions with weather forecasts to provide improved guidance to support winter maintenance decisions. Example of DSS include MDSS, FORETELL and WRS.

2.7.1 MDSS

Maintenance Decision Support System (MDSS) is a type of DSS that integrates current and forecast weather information, with information on current roadway conditions, to provide current road and weather data and forecasts and real-time treatment recommendations specific to winter road maintenance routes (e.g., treatment locations, types, times, and rates), tailored for winter road maintenance decision makers. With the right information, winter maintenance managers can respond proactively by managing the infrastructure and deploying resources in real time. One byproduct of MDSS products is that they will often incorporate several of the earlier mentioned weather information sources into a user-friendly interface, making it useful as a tool for synthesizing weather observations and forecasts.

A variety of products and efforts have been characterized as MDSS. In order to help distinguish what comprises an MDSS, guidance was prepared to assist states in procuring MDSS-compliant technology (41). The following elements are deemed essential in comprising an MDSS:

- External data sources including weather forecasts, observations from RWIS, radar and satellite images and GPS/AVL data from maintenance trucks,
- Road condition and treatment module to predict road surface temperature and snow depths,
- Pavement frost product to predict the occurrence of frost,
- Alert generator to create weather and road alerts based on current and forecast information,
- Treatment update network layer to collect Python Common Gateway Interface (CGI) scripts that are run by the web server in response to a request from the display,
- Thematic Real-time Environmental Distributed Data Services (THREDDS) server,
- Web Map Service (WMS) server, and
- MDSS display.

Several different approaches have been used to develop an MDSS that follows these guidelines. FHWA's functional prototype MDSS capitalized on existing road and weather data sources and state-of-the-art weather forecasting models and data fusion techniques. By integrating measured and forecasted road and weather data with proven rules of practice, MDSS provides winter maintenance personnel with diagnostic and prognostic maps of road conditions by maintenance route. It also provides a decision support tool with treatment recommendations along with anticipated consequences of action or inaction. The functional prototype has been tested through field demonstrations in central Iowa in 2002-03 and 2003-04 (42, 43), and on Colorado's E-470 in 2004-05 (44).

In 2002, a pooled fund study, led by South Dakota and now including twelve other states, formed with the goal of establishing an operational MDSS that meets or exceeds the federal vision of an

MDSS (45). The study contracted with Meridian Environmental Technology to develop the operational prototype. Phase 1 of the study resulted in the development of an architecture, based on evaluating FHWA's functional prototype MDSS and extensive outreach to DOT personnel to understand the requirements of the operational MDSS. The resulting architecture differed from the FHWA functional prototype in that it used "a forecasting technique that integrates computer-based processing and the expertise of professional meteorologists." It does not rely on FHWA Rules of Practice but instead "views each weather-induced situation as unique and the appropriate response is based upon the physics and chemistry of the processes occurring on the pavement surface" (46). Phase 2 of this study targeted the development of an operational MDSS. There were concurrent efforts including fundamental research used for developing and enhancing modules (e.g. chemical concentration/freezing point computation) and software programming and development. Through subsequent project phases, testing has expanded to several hundred test sections during the winter of 2006-07 (47). The purpose of this testing is similar to that conducted on the federal prototype: verifying the reliability of weather and road condition predictions, and assessing the usability of the interface and treatment recommendations.

Other vendors have marketed products with MDSS functionality, including DTN/Meteorlogix, and Vaisala. Evaluations of the pooled fund (Meridian) MDSS and the DTN/Meteorlogix are currently underway.

2.7.2 FORETELL

FORETELL is a multi-state advanced road and weather condition prediction system developed by Castle Rock Consultants that integrates satellite, radar and surface observations with RWIS data, using state-of-the-art NOAA/NWS weather models and decision support displays (48). For instance, the FORETELL application can display the current or predicted precipitation for the area of interest, at a six-mile grid resolution. FORETELL uses NWS data sources, airport sensors, road sensors and mobile platforms. National weather prediction is supplemented by regional weather models covering New England and the Upper Mississippi Valley at greater resolution. Manual road reports are added to the system using the sister system, Condition Acquisition and Reporting System (CARS). CARS is a road reporting system that creates a multi-state database of highway events and acts as the hub of state-wide and regional traveler information systems, bringing multiple agencies together and creating state-wide virtual TMCs (49).

The service provided by FORETELL includes a 24-hour forecast updated four times per day as well as hourly updates known as "nowcasts", and pavement condition predictions (50). FORETELL also uses pager, e-mail, radio and 511 telephone systems to distribute weather and road conditions on demand.

FORETELL uses current observations and regional weather models like rWeather. It does not include decision-support capabilities like MDSS; however, its information dissemination methods were intended to reduce the "swivel-chair integration" problems that first motivated MDSS.

Surveys were conducted to evaluate FORETELL before and after deployment to determine the impact of the system on the weather related activities of highway maintenance operators. During the winter of 1999-2000 and 2000-2001, surveys were conducted focused on six users groups

after the gathering of baseline data in November 1999 (51). Survey results showed that approximately one-third of highway maintenance operators said that they change weather-related decisions based on the FORETELL information provided (e.g., wind speed, wind direction, precipitation, air temperature, pavement temperature, dew point, and pavement condition). Also, over 50 percent of users said they want to continue using the FORETELL in the future. However, less than 20 percent of users were willing to pay for the service (51).

Four states continued to operate FORETELL's regional forecasting models until the winter of 2006-07, when they switched over to using MDSS modeling approaches.

2.7.3 Weather Response System (WRS)

Sponsored by the FHWA and Missouri DOT (MoDOT), the WRS is developed to generate user-tailored data and products, which are provided to MoDOT personnel and allow them to respond to the effects of changing weather in a proactive manner. The overall scope of WRS encompassed broader maintenance activities beyond winter storm response and other operational categories including traffic, incident, and emergency management (52).

MoDOT currently does not have a comprehensive source of weather forecast or road condition information. Instead, MoDOT uses a combination of weather information sources including a small network of 13 RWIS sites around the state, commercial media, Data Transmission Network (DTN) weather radar, the Internet, and intra-agency radio and telephone communications. The design of the prototype WRS is to (52):

- Take advantage of operational weather data and products from the NWS;
- Utilize a variety of weather data sources including traditional NWS sources and emerging products such as the NWS' NDFD;
- Leverage the experience related to user needs and decision support tools developed in the FHWA MDSS project;
- Provide a framework to develop and demonstrate prototype road-weather products tailored for specific operational categories;
- Support the operational decisions of maintenance supervisors and traffic managers in MoDOT; and
- Provide weather data managed by the WRS to traffic management centers (TMCs) and district maintenance facilities in order to evaluate its effectiveness and to identify the needs for additional weather-related decision support tools for transportation management, operations, and maintenance.

The prototype WRS includes several modules: the National Weather Maps module, Statewide Weather Maps Module, Regional Weather Maps Module, Slideshow Module, and Maintenance Planner Module. Each module enables users to obtain specific weather information. For example, the Maintenance Planner Module provides temperature, humidity, sky cover, chance of precipitation, wind speed, and wind direction for a location of interest (52).

2.8 Future Directions

This section introduces some other programs that are under planning or experimental stages. They are expected to provide useful weather information for improving roadway maintenance in the near future.

2.8.1 Vehicle Infrastructure Integration

In 2003, four state DOTs as well as private partners were involved in the first US DOT Vehicle Infrastructure Integration (VII) initiative. Since then, VII has been a hot topic in the ITS arena. VII involves the two-way communication between vehicles and roadside infrastructure as well as from vehicle to vehicle utilizing Dedicated Short Range Communications (DSRC) (53). The vision of this initiative is to have instrumented vehicles and roadside, supported by a communications network, so that data can be exchanged with a nationwide instrumented roadway system.

The major goal of the initiative is from a weather perspective for the weather enterprise to utilize vehicle data to improve weather and road condition products and to provide those products to transportation system decision maker and travelers. Potential weather-related vehicle data that can be collected by VII include ambient air temperature, wind speed, precipitation, pavement temperature, and pavement condition. This could help to provide more complete coverage of current conditions than would be available through any fixed-site observation network.

However, there are several challenges and issues with data detection. For example, it may be possible to use multiple sensors for the same parameter (e.g., air temperature, precipitation) in order to increase accuracy, but some parameters, such as humidity, are not available. Accelerometer data and vehicle speed can be used as a surrogate for direct detection and wind speed, but accelerometer data are difficult to use and steering data are affected by more than crosswind (e.g., road grade). There are also challenges in providing quality control on immense volumes of data on a real-time basis. Sensing advances, data fusion technologies, and statistical approaches are required to reduce or solve these problems (53).

CHAPTER 3. SURVEY OF WINTER MAINTENANCE PERSONNEL

In August and September 2007, the research team distributed an electronic survey through SurveyMonkey (http://www.surveymonkey.com). The questions for the survey are shown in Appendix B. The survey was undertaken to learn mainly about weather information sources for winter maintenance and covered the following five categories:

- Category 1: Respondents' winter maintenance context;
- Category 2: Use of weather information resources;
- Category 3: Winter maintenance operations;
- Category 4: Cost of weather information; and
- Category 5: Assessment of weather information.

Of 133 collected responses, 109 were considered to be valid. (Most of those surveys which were discarded completed less than a fourth of the survey.) The remainder of this chapter focuses on these valid responses.

Survey results from categories 1, 2, 4, and 5 will be summarized in this Chapter. The results from category 3 will be presented in CHAPTER 5 to focus more on how weather information is used in snow and ice control practices. Please refer to the project report of Technical Memorandum 1—Weather Resource Availability, for more details of survey results (54).

3.1 Respondents' Winter Maintenance Context

The respondents were distributed across 25 states in the U.S. and three provinces in Canada. Agencies from these states and provinces cover state or provincial transportation agencies, county/municipal transportation agencies, and private-sector weather information providers. The number of respondents from each state/province is shown in Table 1. Iowa was the largest group surveyed with 43 respondents. The second largest group was from Nevada with 12 respondents. In several states in the U.S. and those three provinces in Canada, only one person responded.

The distribution of level of responsibility is shown in Figure 6. As some respondents had more than one level of responsibility, the total number in the chart is larger than the number of respondents (109). Nine respondents shared both field crew and supervisor roles, two of them were supervisor and maintenance managers, and two had the all the three levels of responsibility. Around one-fifth of the respondents have other responsibilities including, but not limited to winter operations administration, operations manager, statewide operation, general office support, area superintendent, statewide manager, and quality manager. The majority of "others" had the level of responsibility of managers.

There was significant correlation between the level of organizational responsibility and the state or province which the respondent represented. The vast majority of Iowa's respondents were field crew/operators and/or supervisors, while states from which one response was collected were typically represented by maintenance managers. Based on screening of some survey

questions, the research team concluded that the responses of field crews and supervisors were similar enough to each other that they could be combined into one group of 52 respondents, while the other two categories could be combined into a second group of 57 respondents. This grouping helps to reduce the potential of Iowa's large number of responses to hide those responses submitted by other agencies.

Table 1: Number of Respondents from States and Provinces

United States				Canada	
State	*No. of Respondents*	*State*	*No. of Respondents*	*Province*	*No. of Respondents*
Alaska	5	Nevada	12	Alberta	1
California	6	New Jersey	2	British Columbia	1
Colorado	5	New Mexico	1	Ontario	1
Connecticut	2	New York	4		
Illinois	2	North Carolina	2		
Indiana	2	Oklahoma	1		
Iowa	43	Pennsylvania	1		
Kentucky	1	Tennessee	1		
Maryland	1	Utah	1		
Minnesota	1	Vermont	1		
Missouri	2	Virginia	2		
Montana	1	Washington	2		
Nebraska	4				
Total	**108**				

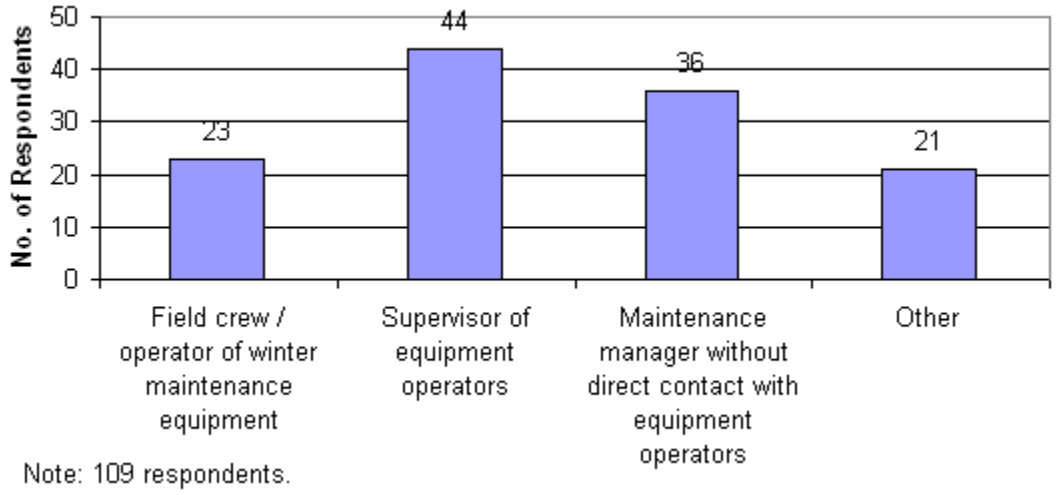


Figure 6: Distribution of Level of Responsibility

Respondents were asked to characterize the types of winter weather they normally experience. As shown in Table 2, over 90 percent of the respondents dealt with snow storms several times per year. The vast majority of respondents also reported experiencing wind and surface ice/frost events. Around half of the respondents experienced extreme low temperature and/or freezing rain several times per year.

Table 2: Experience in Various Types of Winter Weather

Types of Winter Weather	Frequency				
	Never	Seldom	Once per Year	A couple of times per year	Several times per year
Extreme low temperatures (sustained temperatures below 15° F/-10° C)	4	13	4	26	62
Freezing rain	1	15	0	40	53
Snow storms	1	1	1	4	102
Surface ice/frost	1	2	0	16	90
Wind (sustained speeds over 15 mph/24 kmph)	1	0	2	13	93

Note: 109 respondents.

Table 3 presents the frequency at which respondents perceived that field crews, crew supervisors, and maintenance managers consult weather information during winter operations. Crew supervisors had the highest frequencies of consulting weather information; the majority (84 percent) of them used weather information daily or several times per day, while 72 percent of maintenance managers and 55 percent of field crews used weather information at the same frequency. The lower usage of weather information by field crews may reflect that they are generally in the field during winter operations. Field crews were more likely to check weather information when a storm is imminent, since it will likely have direct consequence on their daily work activities.

Table 3: Frequency of Consulting Weather Information

	How often they consult weather information					
	Never	When a storm is imminent	Most winter days	Daily	Several times per day	Don't know
Field Crews	7	16	22	27	28	9
Crew Supervisors	1	4	9	26	66	3
Maintenance Managers	2	9	12	20	40	26

Note: 109 respondents.

3.2 Use of Weather Information Resources

In this part of survey, questions were mainly focused on five different weather information resources including: free weather information sources, private-sector weather information providers, RWIS, road weather observation mesonets, and decision support systems. The definitions of each of these sources in the survey were as follows:

- Free Weather Information Sources refer to sources of weather information which are available to the general public without paying a subscription or peruse fee, such as NWS/NOAA, local television and radio, national or cable TV broadcasts, and free weather information web sites.
- Private-Sector Weather Information Providers refers to for-fee services by which the private sector provides customized weather information (typically forecasts) to an agency.
- RWIS refers to roadside equipment used to measure current weather conditions at the road environment.
- Road weather mesonets combine current weather observations from a variety of sources into a single interface, and often have internal quality control algorithms (e.g. *Clarus* Initiative).
- Decision Support Systems are systems which integrate information about current conditions with weather forecasts to provide improved guidance to support winter maintenance decisions (e.g. MDSS, FORETELL).

The survey results are presented and analyzed based on different survey questions. In the following, for simplicity, free sources will represent free weather information sources, private sector refer to private-sector weather information providers, mesonets denote road weather observation mesonets, and DSS is the abbreviation of decision support systems.

3.2.1 Frequency of Using Weather Sources

Table 4 presents the frequency of using different weather sources for winter maintenance operations by the respondents during last winter. The results show that free weather information sources were the most popular among respondents; only one did not use such sources. The number of respondents that never used a specific weather source increases from left to right of the table. The highest percentage value of the respondents for each weather source is highlighted. In the cases of private sector, RWIS, mesonets and DSS, it should be noted that not all respondents may have access to these sources. In some cases, respondents may have had access to these sources but did not know about them or chose not to use them.

It is worth noting that users of free sources, private sector and RWIS weather information were more than likely to use them at least daily, while users of mesonets and DSS used them less frequently.

Table 4: Frequency of Using Weather Sources

Frequency of Use	Weather Information Source				
	Free Sources	Private Sector	RWIS	Mesonets	DSS
Never	1 (0.9%)	15 (13.9%)	17 (16.0%)	59 (55.7%)	73 (69.5%)
Seldom (Couple of Times Per Season)	2 (1.9%)	7 (6.5%)	9 (8.5%)	7 (6.6%)	10 (9.5%)
Sometimes (Couple of Times Per Week)	11 (10.2%)	11 (10.2%)	9 (8.5%)	17 (16.0%)	8 (7.6%)
Often (Daily)	46 (42.6%)	25 (23.2%)	32 (30.2%)	16 (15.1%)	9 (8.6%)
Always (Multiple Times Per Day)	48 (44.4%)	50 (46.3%)	39 (36.8%)	7 (6.6%)	5 (4.8%)
Total No. of Respondents	**108**	**108**	**106**	**106**	**105**

3.2.2 Use of Weather Parameters about Current Conditions for Winter Maintenance

Weather information sources are able to provide various weather parameters such as air temperature, pavement temperature, and wind. Respondents were asked which ones they consult from each source; the results are displayed in Table 5. As relatively small groups of surveyors used mesonets and DSS for winter maintenance, the numbers of respondents for both weather sources are thus smaller than the other three groups. Each respondent could choose multiple choices for this question and those cells in the "total" rows with percentage values greater than or equal to 60 percent are highlighted. The results from crews and supervisors and those from maintenance managers and others were added up and shown in the table to see if there have significant differences between these two groups.

Air temperature, wind, and precipitation amount and type are weather elements that were used by the majority of the respondents, while relative humidity/dewpoint and visibility information had relatively less usage. While free sources are used by nearly all respondents, the users tend to focus on receiving air temperature, wind and precipitation amount and type information. If they are interested in other weather information such as roadway data, they always seem to prefer getting it from other sources. Thus, the percentage values of pavement temperature, pavement condition, and bridge temperature for free sources are lower than those from other sources.

Simple paired student's t-tests were conducted to see if there are significant differences of using of roadway data between free sources and others. Such tests can be used to compare two small sets of data. The t-tests treated the percentage of respondents consulting free sources for a certain weather parameter as "before" data and the percent of respondents receiving that information from other sources as "after" data. At a 95 percent significance level, the t-test results confirmed that there is a statistically significant difference in the usage of free versus non-free sources for finding out pavement temperature, pavement condition, bridge temperature, and visibility.

Table 5: Weather Parameters about Current Weather Conditions from Different Sources

Weather Parameter	Level of Responsibility	Weather Information Source				
		Free Sources	Private Sector	RWIS	Mesonets	DSS
Air temperature	Field Crews/Supervisors	45	40	39	19	12
	Managers/Others	34	36	36	13	8
	Total	79 (73.2%)	76 (78.4%)	75 (84.3%)	32 (76.2%)	20 (62.5%)
Relative humidity/ dewpoint	Field Crews/Supervisors	13	19	20	8	6
	Managers/Others	26	26	22	7	7
	Total	39 (36.1%)	45 (46.4%)	42 (47.2%)	15 (35.7%)	13 (40.6%)
Pavement temperature	Field Crews/Supervisors	18	35	42	14	13
	Managers/Others	11	24	39	8	8
	Total	29 (26.9%)	59 (60.8%)	81 (91.0%)	22 (52.4%)	21 (65.6%)
Pavement condition	Field Crews/Supervisors	11	23	28	11	10
	Managers/Others	6	13	23	5	7
	Total	17 (15.7%)	36 (37.1%)	51 (57.3%)	16 (38.1%)	17 (53.1%)
Bridge temperature	Field Crews/Supervisors	15	32	38	14	10
	Managers/Others	7	17	21	6	7
	Total	22 (20.4%)	49 (50.5%)	59 (66.3%)	20 (47.6%)	17 (53.1%)
Wind	Field Crews/Supervisors	42	40	38	18	14
	Managers/Others	40	35	28	9	7
	Total	82 (75.9%)	75 (77.3%)	66 (74.2%)	27 (64.3%)	21 (65.6%)
Visibility	Field Crews/Supervisors	14	24	18	14	8
	Managers/Others	18	22	16	6	5
	Total	32 (29.6%)	46 (47.4%)	34 (38.2%)	20 (47.6%)	13 (40.6%)
Precipitation amount and type	Field Crews/Supervisors	47	40	33	21	15
	Managers/Others	47	39	28	10	8
	Total	94 (87.0%)	79 (81.4%)	61 (68.5%)	31 (73.81%)	23 (71.2%)
Total No. of Respondents		**108**	**97**	**89**	**42**	**32**

Note: 109 respondents including 52 field crews and supervisors and 57 maintenance managers and others.

3.2.3 Use of Forecast Weather Parameters for Winter Maintenance

Respondents were also asked about which weather parameters they refer to when consulting forecasting services, including free sources, private sector, and DSS. The results are summarized in Table 6. Those cells that have percentage values greater than 60 percent are highlighted. Similar to Table 5, the results from crews and supervisors and those from maintenance managers and others were added up and shown in the table.

The highlighted values show that the six forecast parameters of air temperature trends, wind/blowing snow, precipitation amount and type, timing/onset of the weather event, intensity and duration of the weather event, and exit timing of the weather event are widely used from these three weather sources. The inputs from group 1 (field crews and supervisors) and group 2 (maintenance managers and others) are very close for these parameters[3].

As in Table 5, the respondents using free sources tended to focus on the mentioned six forecast parameters. They preferred obtaining other forecast information (e.g., pavement temperature trends, bridge temperature) from other sources, especially the private sector. For the forecast information of relative humidity/dewpoint, pavement temperature trends, pavement condition, and bridge temperature, it looks that the respondents from group 2 had less frequent use than those from group 1. For example, a quarter of respondents from group 1 indicated the use of forecast pavement temperature trends, while only 10 percent of group 2 used such information.

[3] DSS was not included in this analysis due to a small sample size (29 respondents).

Table 6: Forecast Weather Parameters from Different Weather Sources

Weather Parameter	Level of Respon-sibility	Weather Information Source			Weather Parameter	Level of Respon-sibility	Weather Information Source		
		Free Sources	Private Sector	DSS			Free Sources	Private Sector	DSS
Do not use for forecasts	G1*	0	0	3	Wind/blowing snow	G1	35	39	12
	G2**	3	2	4		G2	39	36	6
	Total	3 (2.8%)	2 (2.3%)	7 (24.1%)		**Total**	74 (69.8%)	75 (85.2%v	18 (62.1%)
Air temperature trends	G1	37	34	11	Visibility	G1	20	25	9
	G2	35	34	7		G2	21	24	5
	Total	72 (67.9%)	68 (77.3%)	18 (62.1%)		**Total**	41 (38.7%)	49 (55.7%)	14 (48.3%)
Relative humidity/dewpo int	G1	11	19	6	Precipitation amount and type	G1	44	41	15
	G2	26	25	6		G2	51	43	8
	Total	37 (34.9%)	44 (50.0%)	12 (41.4%)		**Total**	95 (89.6%)	84 (95.5%)	23 (79.3%)
Pavement temperature trends	G1	13	30	11	Timing/onset of the weather event	G1	42	42	13
	G2	6	27	8		G2	47	41	8
	Total	19 (17.9%)	57 (64.8%)	19 (65.5%)		**Total**	89 (84.0%)	83 (94.3%)	21 (72.4%)
Pavement condition	G1	12	26	8	Intensity and duration of the weather event	G1	43	38	14
	G2	6	17	7		G2	45	42	8
	Total	18 (17.0%)	43 (48.9%)	15 (51.7%)		**Total**	88 (83.0%)	80 (90.9%)	22 (75.9%)
Frost forecasts	G1	17	36	10	Exit timing of the weather event	G1	40	38	12
	G2	25	34	8		G2	42	39	8
	Total	42 (39.6%)	70 (79.5%)	18 (62.1%)		**Total**	82 (77.4%)	77 (87.5%)	20 (69.0%)
Bridge temperature	G1	13	32	11	Other	G1	2	0	0
	G2	7	16	7		G2	5	2	0
	Total	20 (18.9%)	48 (54.5%)	18 (62.1%)		**Total**	7 (6.6%)	2 (2.3%)	0 (0.0%)
Total No. of Respondents		106	88	29	**Total No. of Respondents**		106	88	29

Note: 109 respondents including 52 field crews and supervisors and 57 maintenance managers and others.
* - Field Crews/Supervisors
** - Managers/Others

3.2.4 Time Scales for the Use of Weather Forecasts

As mentioned before, weather forecasts may be subdivided into decision scales. Table 7 presents the results of the use of weather forecasts under four time scales from nowcast (1-6 hours) to long-term forecasts (more than 5 days). The three types of weather resources correspond to those in Table 6. It can be observed that short-term (6-24 hrs) forecasts from all three sources were most widely used for winter maintenance operations. Many respondents reported using medium-term (24 hr- 5 day) forecasts; these were typically provided by free sources or the private sector. Usage of DSS is primarily for nowcasts and short-term forecasts. Among the four types of forecasts, long-term (more than 5 days) forecasts were the least important frequently used.

Table 7: Time Scales for the Use of Weather Forecasts

Timescale	Weather Information Source		
	Free Sources	Private Sector	DSS
Nowcast (1-6 hrs)	53 (49.5%)	59 (64.8%)	17 (53.1%)
Short-term (6-24 hrs)	80 (74.8%)	75 (82.4%)	22 (68.8%)
Medium-term (24 hr-5 day)	72 (67.3%)	60 (65.9%)	10 (31.3%)
Long-term (more than 5 days)	37 (34.6%)	32 (35.2%)	6 (18.8%)
Total No. of Respondents	**107**	**91**	**32**

3.2.5 Degrees of Satisfaction with Weather Sources

The respondents were asked to report their degrees of satisfaction with the weather sources they used for winter maintenance and the results are provided in Table 8. The highlighted data show that the majority of the respondents were satisfied with four of the weather sources they employed, except that half of those using DSS expressed neutral opinions. The table also presents average weighted scores based on the number of people that responded to a particular source. People were most satisfied with RWIS, with an average score of 3.92; the private sector also has a relatively high score; free sources and mesonets received a slightly lower satisfaction rating.

Table 8: Degrees of Satisfaction with Weather Sources

Level of Satisfaction	Weather Information Source				
	Free Sources	Private Sector	RWIS	Mesonets	DSS
Very satisfied (5)	14 (13.1%)	20 (22.0%)	25 (28.1%)	5 (10.9%)	3 (9.4%)
Satisfied (4)	51 (47.7%)	38 (41.8%)	43 (48.3%)	22 (47.8%)	9 (28.1%)
Neutral (3)	38 (35.5%)	30 (33.0%)	13 (14.6%)	18 (39.1%)	16 (50.0%)
Dissatisfied (2)	3 (2.8%)	1 (1.1%)	5 (5.6%)	0 (0.0%)	4 (12.5%)
Very dissatisfied (1)	1 (0.9%)	2 (2.2%)	3 (3.4%)	1 (2.2%)	0 (0.0%)
Average Score	***3.69***	***3.80***	***3.92***	***3.65***	***3.34***
Total No. of Respondents	**107**	**91**	**89**	**46**	**32**

3.2.6 Other Resources

Roughly a quarter of the respondents identified weather information sources beyond those described earlier; these are listed in Table 9. Some of them in the table are actually included in the above weather sources. For example, TV/radio and newspapers are free weather information sources.

Table 9: Other Weather Sources

- On-vehicle sensors
- TV / radio
- Nature
- Communication with other shops
- Newspaper
- Vehicle thermometers
- Local television web sites
- News/weather reports
- Snotel sites
- *Farmers Almanac*
- Ca Dept of Water Resources Flood Management
- Camera located at key areas that show existing road conditions
- Road Watch Temperature Sensors
- Free radar and satellite photos from Environment Canada website
- Look out the window or step outside
- In house road weather meteorologist
- Field reports from workers.
- State climatologist & NOAA, Tidal telemetry system

Survey results indicated that those respondents using TV, radio, newspaper, and local weather channel were generally neural or dissatisfied with weather information provided by these sources. Other respondents were generally satisfied with the weather sources they used.

3.2.7 Other Survey Results

Table 10 presents respondents' projections of future use of different weather sources. The majority of those respondents using free weather information sources, private-sector providers, mesonets, and "other" sources indicated that they would have no change in the future. Around half of the respondents anticipate using RWIS more frequently in the future, with around half anticipating no change in use. Around one-third of respondents would like to use DSS more frequently, but 15 percent of them indicated less frequent use in the future. In general, however, respondents indicate that they do not anticipate reducing their reliance on these weather information sources in the future.

Table 10: Future Use of Various Weather Information Sources

Level of Future Use Compared to Present	Weather Information Source					
	Free Weather Information Sources	Private-Sector Weather Information Providers	RWIS	Road Weather Mesonets	Decision Support Systems	Other
Less Frequently	3 (3.3%)	5 (5.5%)	2 (2.2%)	9 (9.9%)	14 (15.4%)	22 (24.4%)
No Change	70 (76.9%)	69 (75.8%)	45 (49.5%)	65 (71.4%)	47 (51.7%)	64 (71.1%)
More Frequently	18 (19.8%)	17 (18.7%)	44 (48.4%)	17 (18.7%)	30 (33.0%)	4 (4.4%)

Note: 90 respondents for the "Other" source and 91 for the rest.

The respondents were asked to denote the importance (from the first most importance to the fifth most importance) of weather parameters within different time scales (from current observations, nowcast, short-term forecasts, and medium-term forecasts to long-term forecasts). The respondents were allowed to have multiple choices for each importance ranking. To better display the results, average weighted scores were calculated for each parameter in each time scale, based on the number of votes and assigned weights for different importance ranking (5 points for the first most important and 1 point for the fifth most important).

The results are presented in Figure 7. Current observations and nowcast (1-6 hours out) are of most importance. After the nowcast time horizon, the importance of parameters decreases with the increase of time scale. There are no significant differences of average weighted values between parameters, but the parameters of precipitation begin/end time and precipitation type seem to have higher importance values than other parameters.

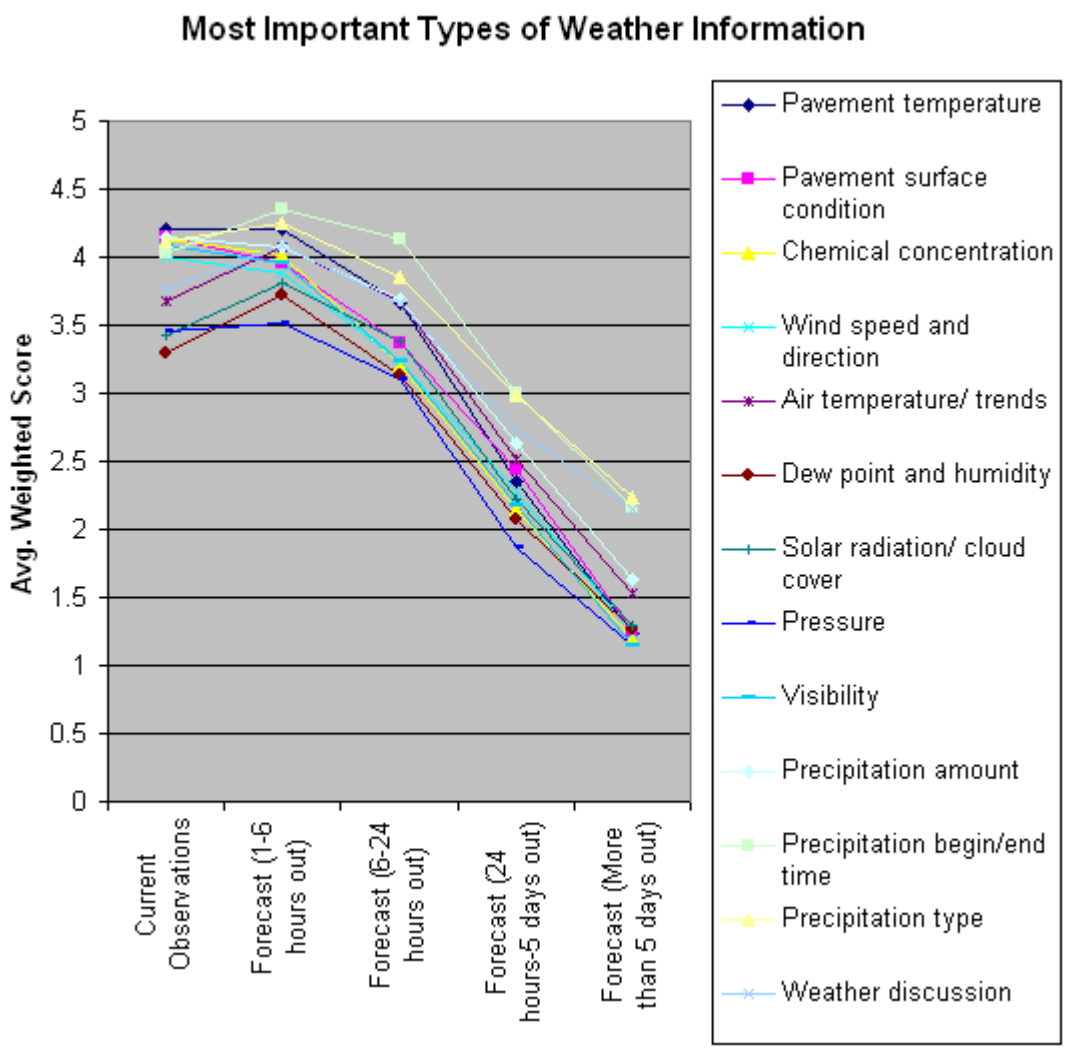


Figure 7: Most Important Types of Weather Information for Different Time Scales

3.3 Cost of Weather Information

State and local agencies spent significant money annually in winter maintenance: over $2 billion in the United States alone (1). One part of the expenses relates to acquiring weather information, including the costs of private-sector forecasting services, RWIS design and construction and RWIS operations and maintenance. The estimated percentage of total winter maintenance cost spent in obtaining weather information is summarized in Table 11.

Table 11: Percentage of Maintenance Cost Spent in Obtaining Weather Information

Less than 1%	1-5%	5-10%	10-20%	More than 20%	Don't know
21	17	3	0	2	44

It is noteworthy that although 87 respondents answered this question, approximately half of the respondents did not know the percentage of maintenance cost on weather information. Most of the other respondents indicated that the percentage was less than 1 percent or between 1 and 5 percent.

The cost of weather information includes several components, and respondents were asked to rank these components by cost. Table 12 shows the ranking of cost of five components. The survey results from 37 respondents show that the most expensive component of weather information cost is the design and installation of RWIS, followed by communications to RWIS, maintenance of RWIS, obtain of forecasts and interpretation of forecasts in sequence.

Table 12: Cost Components of Weather Information

	Designing and Installing RWIS	Communications to RWIS	Maintenance of RWIS	Obtaining Forecasts	Interpreting Forecasts (1)
Most expensive	25	3	0	6	3
2nd	4	14	11	4	4
3rd	3	11	17	3	2
4th	2	7	5	20	5
Least expensive	3	2	4	4	23

Note: 37 respondents

(1) Interpreting forecasts refers to the cost involved in taking a traditional weather forecast and translating it into information that could be used to direct winter maintenance decisions. This may include tools such as private-sector weather information services and decision support systems.

As mentioned earlier, the utilization of road and weather information can help maintenance personnel improve decision making and reduce maintenance costs. From the respondents' points of view, Table 13 presents the results of the effects of weather information in winter maintenance costs. This is to show whether or not weather information can reduce costs related to staffing, chemicals/materials, and equipment. In addition to the overall results from all the respondents, the answers from field crews and supervisors and those from maintenance managers and "others" were combined together. Both groups have 41 respondents.

Based on the results from all respondents, the use of weather information is perceived to decrease applications of chemicals/materials. The majority of respondents indicated that the use of weather information did not affect the cost of staffing and equipment; however, approximately 40 percent of the maintenance managers/others thought that the cost of equipment would be reduced. In addition, about one-third of managers/others indicated that the use of weather information could reduce staffing cost.

In comparing the number of respondents who marked "don't know" between field crews/ supervisors and managers/others, it appears that maintenance managers tend to have a better understanding of winter maintenance costs.

Table 13: Effects of Weather information in winter maintenance Costs

Resource Category		Effect of Weather Information on Resource Usage					
		Increased greatly	Increased	No change	Decreased	Decreased greatly	Don't know
Staffing	Field Crews Crew/Supervisors	0	2	19	6	1	13
	Maintenance Managers/Others	2	2	19	10	1	7
	Total	**2**	**4**	**38**	**16**	**2**	**20**
Chemicals / Materials	Field Crews Crew/Supervisors	2	7	8	8	3	13
	Maintenance Managers/Others	2	4	7	19	1	8
	Total	**4**	**11**	**15**	**27**	**4**	**11**
Equipment	Field Crews Crew/Supervisors	2	7	13	5	1	13
	Maintenance Managers/Others	2	9	10	13	0	7
	Total	**4**	**16**	**23**	**18**	**1**	**20**

Note: 82 respondents including 41 field crews and crew supervisors, and 41 maintenance managers and others.

3.4 Assessment of Weather Information

Respondents were asked to characterize how weather information could be improved in the future to better serve winter maintenance requirements. The survey allowed respondents to prioritize up to five weather information improvement needs; these results are summarized in Table 14 . Respondents overwhelmingly indicated that the most pressing need is better forecasts about precipitation timing, type and amount. The second- and third-most needed improvements are to provide more timely forecasts and improve proactive warning of storm events. From the column of second-most needed improvement, the need for better knowledge of pavement

temperatures was also a concern of many respondents. It seems that the improvement of access to a forecaster is not as important of a concern as others.

Table 14: Needs to Improve Weather Information

	More timely forecasts	Improved access to a forecaster	Improved proactive warning of storm conditions	Better knowledge of pavement temperatures	Better forecasts about precipitation timing, type and amount
Most needed improvement	16	2	10	12	60
2nd	29	10	12	21	18
3rd	16	12	36	13	6
4th	3	7	4	4	0
Fifth-most needed improvement	3	5	5	4	1

Respondents were asked to identify, from a list, the top three barriers they perceived in their usage of weather information. The respondents were allowed to choose multiple ones (barriers) for each rank. Table 15 summarizes the votes for each rank and weighted scores for each barrier, assuming 3, 2, and 1 point for the biggest, 2nd, and 3rd barrier, respectively. According to this ranking process, the biggest barrier to the usage of weather information is the reliability and accuracy of weather information received. Three other major issues are the insufficient detail of weather information, the cost of obtaining weather information, and the trustworthiness of weather information, which is not good enough to help make winter maintenance decisions. Under the "other" category, respondents were allowed to indicate other barriers. Some answers included funding, resistance to change among some maintenance superintendents, and decision-makers' knowledge of best practices to deploy based on weather information and forecasts.

Table 15: Barriers to Using Weather Information

Barrier	Biggest barrier (3)	2nd (2)	3rd (1)	***Weighted Score***
The weather information we receive is not trustworthy.	19	14	16	**101**
The information sources that we want to use (e.g. private-sector, RWIS) would cost too much.	17	6	24	**87**
The weather information available to us doesn't give us sufficient detail to help determine winter maintenance actions.	9	18	23	**86**
Weather information is not trustworthy enough to introduce changes in winter maintenance operations.	13	15	15	**84**
I don't have data on the benefits we can achieve through investing in weather information products and services	7	12	20	**65**
I don't know how to use all of the weather information I receive.	7	5	21	**52**
We have communications challenges with our weather information sources, so information can not be interpreted into directions in time.	3	9	21	**48**
The weather conditions and road surface conditions are quite consistent, so forecasting is not so necessary.	3	5	17	**36**
There are liability concerns if we acquire more or better weather information.	4	3	18	**36**
Other	8	2	4	**32**

The survey finally sought to learn about the perceived benefits of using weather information for winter maintenance; the number of votes for each benefits and weighted scores are shown in Table 16, assuming 3 points for each respondent that chose a specific benefit as the biggest benefits, and 2 and 1 points for the 2nd and 3rd biggest benefits. The results indicate that the biggest benefit of using weather information is responding to winter storms in a more timely and accurate pattern. In addition, other big benefits also include better preparation for storms, improved roadway clearance time, and reduced usage of chemicals/materials. Other benefits include reduced usage of chemicals and materials, reduced labor cost (including overtime), and more accurate staffing and budget plans for entire season. Several respondents indicated that they have used weather sources and have benefited from this. Although the benefits are not quantified at this point, the survey results do provide positive feedback from respondents regarding this issue.

Table 16: Benefits of Using Weather Information

Benefits	Biggest benefit (3)	2nd (2)	3rd (1)	***Weighted Score***
More timely and accurate response to winter storms	55	7	5	**184**
Better preparation for storms, including scheduling of crews and preparation of equipment	25	25	6	**131**
Improved roadway clearance time	24	15	20	**122**
Reduced usage of chemicals and materials	19	16	15	**104**
Reduced labor costs, including overtime	13	15	12	**81**
More accurate staffing and budget plans for an entire season	12	8	12	**64**
Reduced equipment usage and associated costs	9	8	11	**54**
Other	4	1	4	**18**

Note: 67 respondents.

3.5 Summary

This chapter described the use of various weather information sources by winter maintenance personnel. The results have been assembled from a review of relevant literature and surveys of winter maintenance personnel.

Although the team identified others, the research team focused its investigation on five primary types of weather information sources: free sources, private-sector services, RWIS, mesonets, and DSS. Among winter maintenance personnel, free weather information sources, private-sector weather providers, and RWIS were the most widely used weather information sources. The other two sources, the road weather observation mesonets and DSS, have fewer users; they usually collect road and weather data from two or more other sources such as NWS and RWIS, and fuse them to generate information of interest for winter maintenance. Private-sector weather providers, who act similarly to mesonets and DSS, collect weather data from NWS or other sources to provide specialized information of current weather conditions and/or forecasts. Thus, free weather information sources and RWIS are the two primary direct sources for collecting road weather information.

Cost considerations and easy access contribute to the wide use of free weather information sources. However, these sources may have problems with timeliness and a lack of detail, which may result in the use of inaccurate weather information. Based on the survey of winter maintenance professionals, the accuracy of weather sources is the biggest barrier preventing the use of weather information.

Several sources such as AWOS, ASOS, and RWIS, are able to detect surface conditions. AWOS and ASOS are designed to collect meteorological data to assist the aviation community, while RWIS are designed to target the roadway environment. This demonstrates the importance of using data collected from RWIS to improve winter maintenance decision making with safety, environmental, and economic considerations. The quality of road weather forecasts will be restricted without inputs from ESS.

Air temperature, wind, and the type and amount of precipitation are primary parameters of current and forecast weather conditions. Road weather elements such as pavement temperature, bridge temperature, and pavement conditions are also widely used in winter maintenance. In addition to these, winter maintenance personnel are highly concerned with forecasts of the onset, conclusion, intensity, and duration of storm events. The importance of weather forecasts decreases with the scale of time from nowcasts, to short-term, medium-term, and long-term forecasts.

One barrier to using private services and RWIS is the cost. For RWIS, the design and installation as well as the communications to RWIS are the highest cost components. Design and installation are one-time costs, however, and ongoing costs are perceived to be much smaller. The majority of the post-installation costs are related to maintenance. Survey responses indicated that the percentage of winter maintenance budgets spent on obtaining weather information is relatively low (less than 1 percent or between 1 and 5 percent).

The most noticeable benefit of using weather information for winter maintenance is reducing maintenance cost. The perception that using weather information could save on staffing, materials/chemicals and equipment costs was more likely to be reported by maintenance managers than by field crews/supervisors. It is anticipated that through improving the accuracy of weather information, more money will be saved for winter maintenance. For RWIS, the benefits are not constrained to winter maintenance. State and local agencies are sharing weather data with a broader range of public and private users, who can also benefit from the deployment of RWIS.

Table 17 presents a summary of key attributes of the five major weather information sources highlighted in the winter maintenance personnel survey. The table uses several attributes such as target audience, extent of use, and cost, to make a comparison of them.

Table 17: Summary of Weather Information Resources

		Free Sources	Private Services	RWIS	Mesonets	DSS
Target Audience		• Public	• Maintenance Personnel • Public	• Maintenance Personnel • Public	• Maintenance Personnel • Public	• Maintenance Personnel
Timeframe		• Current conditions • Forecasts	• Current conditions • Forecasts	• Current conditions	• Current conditions	• Current conditions • Forecasts
Level of interpretation		Low	High	Low	Varies	High
Extent of Use		Wide	Wide	Wide	Moderate	Moderate
Most frequently used weather parameters (1)	Current weather conditions	• Precip. amount and type • Air temperature • Wind	• Precip. amount and type • Air temperature • Wind	• Pavement temperature • Air temperature • Wind • Precip. amount and type	• Precip. amount and type • Air temperature • Wind • Pavement temperature	• Precip. amount and type • Pavement temperature • Wind • Air temperature • Pavement condition
	Forecasts	• Precip. amount and type • Intensity and duration of the weather event • Timing/onset of the weather event • Exit timing of the weather event • Air temperature trends • Wind/blowing snow	• Precip. amount and type • Timing/onset of the weather event • Intensity and duration of the weather event • Exit timing of the weather event • Wind/blowing snow • Frost Forecasts • Air temperature trends	N/A	N/A	• Precip. amount and type • Intensity and duration of the weather event • Timing/onset of the weather event • Exit timing of the weather event • Pavement temperature trends • Air temperature trends • Bridge temperature • Frost Forecasts • Wind/blowing snow • Pavement condition
Level of Detail	Meteorological data	Regional	Regional or Site-specific (2)	Site-specific	Regional or Site-specific (2)	Regional or Site-specific (2)
	Road Conditions	N/A	Site-specific (3)	Site-specific	Site-specific (3)	Site-specific (3)
Timeliness		May have time lag	In time	In time	In time	In time
Cost		Free – Low	Low - Medium	Medium	Medium	Medium

(1) In order of popularity, mentioned by at least 60 percent of respondents
(2) Depending on which weather sources used.
(3) With information collected from road equipment.

CHAPTER 4. SURVEY OF METEOROLOGICAL COMMUNITY

In October and November 2007, the research team interviewed members of the public and private meteorological community. Interview questions are shown in Appendix C. The purpose of the interviews was to ensure that this research project included adequate representation of weather information sources. Members of the meteorological community were asked to provide input on:

- Category 1: Interviewees winter maintenance context;
- Category 2: Systems and data provided;
- Category 3: Cost to the winter maintenance community; and
- Category 4: Factors that encourage and discourage use.

A total of ten interviews were conducted: five with public agencies, four with private-sector firms, and one organization that provides both public and private weather information (see Table 18). All interviewees were located in the U.S. with the exception of one public weather information provider from Canada. Two interviews were conducted with employees of the same public weather information provider, but the employees had differing positions within the organization.

Table 18: Organizational Affiliations of Interviewees

Public Weather Information Providers	Number Interviewed
Environment Canada	1
National Center for Atmospheric Research (NCAR)	2
National Weather Service (NWS)	1
National Oceanic and Atmospheric Administration (NOAA)	1
Northwest Weather & Avalanche	1
Private Weather Information Providers	
Accu-Weather	1
DTN/Meteoroligix	1
Northwest Weather Net	1
Quixote	1
Total Number Interviewed	10

The distribution of the level of responsibility varied greatly between those interviewed, including meteorologists, program managers, program directors, a marketing manager, and president and or founder of the company. The amount of time the interviewees have been providing services to the surface transportation community ranged from 2.5 to 30 years, with their affiliated companies providing weather information from between 4 and 60 years.

4.1 Systems and Data Provided

Interviewees were asked to provide information on the types of data they provide, the geographic coverage and level of detail of the data, and how the information is provided related to

observational data and forecasts. Observational data is collected from sensors and equipment that monitor environmental parameters, e.g. air temperature and radar, such as a meteorological station. Forecasts predict weather conditions by analysis of current and historical meteorological data, or observational data.

4.1.1 Types of Data Provided

The types of observational data provided can be broken down into two categories: atmospheric and at the pavement surface. Atmospheric data that can be collected includes air temperature, relative humidity, wind speed and direction, precipitation type and amount, dew point, visibility, solar radiation, and satellite and radar imagery. Atmospheric data is collected from 5-30 ft above the pavement surface. Pavement surface data that can be collected includes pavement temperature, pavement condition, presence of deicing products, and sub-surface temperatures.

Forecasts can be generated for any atmospheric and pavement surface parameter that is measured. Forecasts are generally provided in three time frames: short-term (up to 24 hours), medium-term (24 hours-5 day), and long-term (5 or more days). The level of detail and degree of accuracy of forecasts diminishes as one projects farther into the future.

Public and private weather information providers use a wide range of data sources other than observational data they generate themselves. Generally these are free public sources such as ASOS, RWIS, DOT web sites and cameras, Mesonets, and utility companies.

4.1.2 Geographic Coverage and Level of Detail

The geographic coverage and level of detail for observational data and forecasts was consistently reported to be national or international down to point-specific. Public weather information providers generally provide national to local level information, while private weather information providers generally provide more regional to site-specific information. The location of the weather information providers does not necessarily coincide with where the observational data or forecast is collected and reported.

The level of detail for most atmospheric and pavement surface parameters is point-specific. Observational data can be used extrapolate out beyond the locations where the data is collected. Based on interview responses, optimum interpolation between sites is done more on a state to local level, rather than site specific. Satellite and radar data has a resolution range from 1.5 to 7.5 miles (2.5 to 12 km) for observational data and forecasts for the entire U.S.

4.1.3 How is the Information Provided?

The observational data and forecasts are provided via the Internet on open or secure sites as well as e-mail, NOAA/weather radio, fax, telephone, Java interface, pager, personal digital assistants (PDA's) or hard copy via the mail. The most commonly used methods to disseminate information by private weather information providers are Internet, e-mail, telephone and fax. Interviewees commented that they will provide the information any way the customer would like to have it.

Alerting services are also an option provided by private-sector weather information providers.

4.2 How the Winter Maintenance Community Uses Weather Information

As noted earlier, the time frames of information provided by the public weather information sources range from nowcasts (1-6 hrs) to long-term (more than 5 days). The private-sector weather information sources generally provide shorter time frame forecasts, with higher demand for nowcasts, short-term (6-24 hrs), and medium-term (24 hr-5 day) forecasts. Both the public and private-sector weather information providers have had requests for seasonal and historic climate data.

Interviewees were asked to comment on how they perceive the information they provide is used. The responses were very similar between all interviewees and can be broken down into two categories: strategic planning and decision-making. Strategic planning includes pre-treatment or anti-icing options, staging of equipment, the number of personnel to deploy, and shift planning. Strategic planning generally utilizes the medium-term forecasts (24-48 hrs). Decision-making includes material decisions, directing resources, liability, road closures, avalanche control, and information tailored for a tactical response. Decision-making applications utilize the nowcasts and short-term forecasts.

Interviewees also stated that the level of use "varies based on how proactive the folks are; the more training they receive the more they use it. MDSS has been a great success for this." Another comment suggested that the use of the information greatly depends on the application.

4.3 Costs to the Winter Maintenance Community

Interviewees were asked if their services were provided for a fee, how the fee is established, and to provide a typical range of fees that would be associated with a state transportation agency.

4.3.1 Weather Information at No Charge

There is large amount of weather information that is provided to the public at no cost. This information may come from a government organization, a private company, a not-for-profit or cooperative organization. This information is generally provided on the Internet, over the radio, or television.

Government organizations that provide weather information to the public, e.g. NWS, generally provide the information at no cost, as the cost to generate the information is paid for with tax dollars. However, these organizations may charge a one-time use fee or a rate per minute to provide historic data or to speak with a meteorologist. These fees are charged to recoup the costs associated with the request. These organizations do not limit the number of users at one time.

Not-for-profit or cooperative organization that provide weather information to the public may get funding from a variety of federal, state, local and private sources. The Northwest Weather & Avalanche Center (NWAC) is a cooperative organization that provides information to the public as well as private organizations. The information provided by NWAC is funded with federal, state, county and private money. Each co-op member pays $10,000 to $90,000 annually. In 2007

federal agencies paid 36 percent, state agencies paid 43 percent, county agencies paid 10 percent, and private companies or groups paid 11 percent of the 2007 budget (55). These numbers do not reflect in-kind services that have been provided. Washington State Department of Transportation (WSDOT) is a coop member of NWAC and claims considerable annual savings ranging from $180,000 to $330,000 each year through usage of the program (56). These organizations do not limit the number of users at one time.

4.3.2 Weather Information for a Fee

All of the private weather information providers interviewed charged a fee for some or all of their services. How the fee is established varies based on the products and services provided. The companies that only provide observational data equipment may charge a one-time fee for the products. One interviewee reported $25,000 to $80,000 as a one-time fee for RWIS. This company also rents RWIS for a monthly fee, providing current and historical data. Maintenance and service can be contracted out or provided for an additional fee.

Companies that provide observational data equipment and forecasts or only forecasts charge fees that range from $5 to $10,000 a month, while for seasonal or yearly contracts a fee of $40,000 to $126,000 for state wide contracts. Fees quoted by interviewees for weather information provided to cities and counties were much lower than for high-level information provided to states.

Interviewees stated that the fees are established based on a proposal or bid process, where most customers pay a single fee for everything, which generally includes an unlimited number of users. Some companies may charge a per-user fee which may in effect limit the number of users. All fees are dependent on the scale and scope of the services provided.

4.3.3 The Fuzzy Line Between Free and for a Fee

Providers of weather information cover the spectrum in terms of the information provided and whether or not there is a fee. Environment Canada is an organization that generally provides information at no cost to the public, but will set up contracts with larger companies to provide specific information for a fee. The cost of this service varies greatly and depends on the services requested. Another example would be AccuWeather, a private-sector weather information provider that provides a basic website that provides weather information for the public at no charge, which is paid for by advertisers.

4.4 Factors that Encourage and Discourage Use of Weather Information

The interviewees were asked to provide information on what factors they feel encourage and discourage the use of weather information in surface transportation.

4.4.1 Factors that Encourage Use

The responses focused around a few main themes: savings in terms of cost, time/staff, and materials; increased traveler safety; and meeting the public's expectations in terms of LOS. Interviewees commented that the surface transportation industry wants to see "return on their investment, the ability to make effective and efficient use of staff, equipment and crew

scheduling." Another interviewee commented "that they save more money by using a weather forecast service than it costs them," adding that "public safety is increased, and we help them meet their mandated missions."

Other responses that were only mentioned once include: improved data from the weather industry, any information is better than no information, protecting the environment, more detail and provided guidance, and the increasing cost of road closures and accidents.

4.4.2 Factors that Discourage Use

Two main themes that discourage the use of weather information were mentioned by interviewees: overhead and set-up costs, and training and use of the data by staff. One interviewee commented that surface transportation "budget is very limited. These services are not cheap." Another interviewee commented that "road crews need to be educated and some folks are resistant to change." The need for a cultural change at the state level was mentioned where "states are reluctant to modify staffing and equipment based on the new information and therefore is not realizing the full benefit of the tools."

4.4.3 Costs and Benefits

Interviewees were asked to qualitatively assess the benefits and costs of the weather information they provide to the surface transportation community. Provided below are some of the responses to the question.

> *Starting ten years ago, with each year it is getting more accepted and gets more detailed, more cost-effective and we get better coverage.*
>
> *Comparatively, what states pay for weather services is an order of magnitude better in terms of what is provided. We provide good, valuable information. The real crux of the issue is the ability of the agency to take advantage of these tools. Costs have decreased over time; the market has driven more product for less price.*
>
> *We look to provide customers with information they need to handle winter events, to strengthen their effectiveness. This will help them save time and lives. The system makes the roads safer and more effective, keeps businesses going and goods and services moving through out the state.*
>
> *We help them reduce costs and manage resources, in terms of support.*
>
> *Benefits include better planning and staffing, reduced employee costs, more efficiency, bottom line increase, motorist safety. The benefits outweigh the costs.*
>
> *There are state agencies that spend $10,000 every hour on the clock, and if we can save them hours, we can easily show cost savings. We know that we save them hundreds of hours.*

CHAPTER 5. WEATHER INFORMATION IN SNOW AND ICE CONTROL

The previous two chapters focused on identifying the weather information resources that are in use by the winter maintenance community. The purpose of this chapter is to focus more on how weather information is used to support winter maintenance.

The research team conducted a literature review in order to better understand the effects of weather information in winter maintenance operations by defining methods of snow and ice control and the main users of weather information within the transportation agencies. The literature review included looking at the evolving role of weather information in road maintenance operations from pre-storm preparations, to treatment strategies during a storm, proceeding to post-storm cleanup activities.

As mentioned earlier, the research team conducted two surveys: one survey focused on winter maintenance personnel, while the other focused on outreach to the meteorological community. The survey of winter maintenance personnel was undertaken to learn more about weather information sources available for winter maintenance and covered the following five themes: respondents' winter maintenance context, use of weather information resources, winter maintenance operations, cost of weather information, and assessment of weather information. Only those questions related to winter maintenance operations are discussed in this chapter.

5.1 Background on Snow and Ice Control

FHWA's Road Weather Management Program defines "weather-related crashes" as occurring in the presence of rain, sleet, snow, fog, wet pavement, snowy/slushy pavement, and/or icy pavement. This definition encompasses both atmospheric weather conditions and the resulting surface conditions that impact roadway users. On that basis, approximately 25 percent of the 6.4 million crashes that occur each year can be attributed to weather (57). Further, the U.S. DOT attributes 15 percent of all transportation system congestion to snow, ice, and fog (58). Appropriate winter highway maintenance can improve road safety and mobility by maintaining appropriate friction levels on the pavement surface mainly by the three methods of scraping and/or plowing, application of abrasives, and application of chemicals (59).

To best utilize these winter maintenance tools accurate and on time weather information and forecasts are critical. Traditional weather data is measured about 30 ft (~10 m) off the ground, providing information on lower atmosphere meteorological conditions. Atmospheric data collected from National Weather Service (NWS) or similar weather stations typically represent the regional environment and not the road environment. However, conditions on the pavement surface may be very different from those measured in the atmosphere. The roadbed is able to more effectively hold cold and heat than the air above the roadbed. This means that cold pavement may persist long after the air has warmed up (perhaps allowing precipitation to freeze on contact), or that warmer pavement can cause frozen precipitate to melt when it hits the ground. Vehicular traffic can also have both positive and negative impacts on pavement subject to snow

and ice conditions. The tires can compact, abrade, displace, and disperse snow, and the heat generated from tire friction, engines, and the exhaust systems can add measurable heat to the pavement surface (58). Traffic wheel passages can help speed the generation and action of brine on chemically treated snow and/or icy pavements. However, they can also cause the applied chemicals and abrasives to blow or spray off the road. Since snow and ice control practices focus on the road surface, providing both atmospheric and pavement surface data allows winter maintenance personnel to make the best informed decision for the road treatment.

The decision to treat roadways is based on real-time data, nowcasts, and forecasts. Current knowledge of the pavement surface conditions is necessary for making an informed decision on the treatment method and materials. Pavement surface parameters used to make treatment decisions include pavement temperature, whether the pavement is wet or dry, the chemical composition of the solution on the pavement, and the forecasted pavement temperature. Atmospheric parameters used to make treatment decisions include air temperature, dew point and/or relative humidity, solar radiation, precipitation type and amount, wind speed and direction, and barometric pressure. Pavement surface temperature is critical for making accurate treatment decisions, and the air temperature trend is also important to track because pavement temperature will usually follow the general air temperature trend within a few hours depending on the difference in the air temperatures, the amount of solar radiation, wind, and the characteristics of the road (60).

Winter maintenance personnel have resource constraints on staffing, equipment and chemicals/materials. Consequently, the decision of when and how to treat roadways is also filtered through an agency's LOS. The LOS here is defined as an operational set of guidelines and procedures that determine the timing, type, and frequency of the treatments (61). The LOS can then be characterized by the level of effort, priority of the treatment, types of treatments, and the results in terms of pavement conditions during and after storm events. For example, the LOS can be characterized based on average daily traffic (ADT) or location. The defined LOS categories often have specific treatments assigned to them. Many DOTs have a "bare road" policy that determines their LOS.

The method of treatment for the pavement surface is based on the storm cycle time, available materials, weather, pavement and site conditions, and traffic considerations (61). The specific character and intensity of weather events influence the effectiveness of chemical treatments for snow and ice control, how long they will remain effective, and how frequently the roads can and should be plowed.

There are several strategies that can be used to control snow and ice on roadways. To avoid road closures, maintain mobility, and reduce crash risk, transportation agencies will seek to increase the friction coefficient of the roadway through application of sand or removal of frozen precipitation via mechanical or chemical means. The methods used will vary depending on the weather conditions present, the options available to the agency, the timing and other site specific factors, and the prescribed LOS employed by that agency. The methods may include sanding, plowing, deicing and anti-icing or closing roads. Multiple methods may be employed at once or over the course of a storm event.

Using the most appropriate chemical and application rate for the condition, scheduling only plowing, or choosing to do nothing can all be informed decisions based on pavement and weather information. The following sub-sections highlight the chemical and mechanical methods used to treat roads in the presence of snow and ice.

5.1.1 Mechanical Methods

Mechanical methods focus on removal of snow through plowing and/or friction enhancement through sanding. Regardless of the specific means, the use of mechanical methods is generally reactive in nature, and seeks to address winter precipitation which has already bonded to the roadway surface to some degree.

The mechanical removal of snow and ice involves the removal of accumulated material by physically plowing, brooming, or blowing without the use of snow and ice control chemicals (61). Varying equipment and configurations of plowing include snow plow trucks, V plows, reversible plows, tandem or echelon vehicle formations, wing plow and snow blowers. The V plows are used for deep snow or heavy drifts, reversible plows are used to move snow to the left or right side of the truck, tandem or echelon vehicle formations are used to clear multiple lanes simultaneously, wing plows are used to clear shoulders or sides of roadways, and snow blowers are used to clean up snow accumulation (62, 63). The location and angle of the plow may vary between trucks and/or road condition as well as the type of blade (60).

Increasing the coefficient of friction or friction enhancement is a strategy in which abrasives or a mixture of abrasives and a chemical are applied to the plowed or scraped roadway surface that may have a layer of compacted snow or ice already bonded to the pavement surface (64). The most common technique for enhancing friction is to apply abrasive materials such as sand, cinders, ash, tailings, and crushed stone/rock (61). This strategy is used to provide an increased level of friction for vehicular traffic, although this increase may be short-lived. Abrasives only increase the friction coefficient and do not act as ice-control chemicals in and of themselves.

Abrasives can be applied straight or with varying amounts of liquid or solid snow and ice control chemical in a mixture. The addition of chemicals to abrasives is thought to help them stick to the road better and therefore last longer on road. Solid chemicals can be mixed directly into the abrasive stockpiles, and liquid chemicals can be sprayed onto the abrasives as they are being applied to the road, or while the stockpile is being created (61). Warm water can also be applied to abrasives to help them stick to the road.

Application recommendations for abrasives reported in the NCHRP Report 577 for pre-wet, dry, or salt/sand blends range from 500 to 6,000 pounds per lane mile (lbs/l-mi) (64). When using pre-wet versus dry abrasives, there appear to be no temperature constraints; on the other hand, salt/sand blends are limited to use when temperatures range from 0° to 32° F (-18° to 0° C) (61, 65).

5.1.2 Chemical Methods

Chemical methods of snow and ice removal disperse chemicals on the road bed so that, through their reaction with the winter precipitate and/or roadbed, the pavement surface condition is

improved. To generate the right chemical reaction, it becomes more necessary to know the current and future conditions of the roadway environment, including pavement temperature and chemical concentration. Therefore, the use of chemical methods will generally require a greater level of precision and accuracy with respect to weather information sources.

5.1.2.1 Deicing

Deicing is a reactive measure of snow and ice control taken after precipitation has reached the roadway. This method entails removing compacted snow or ice already bonded to the pavement surface by chemical means (61, 64). Deicing generally involves the application of solid chemicals or pre-wet solid chemicals.

Deicing as a snow and ice control measure works in most weather and traffic conditions, and locations. Application rates for deicing reported in NCHRP Report 577 for solid and pre-wet solids range from 200 to 700 lbs/l-m with a working temperature range of 32 to 0 degrees F (0° to -18° C) (61, 64, 65). These are general guidelines with application rates varying based on meteorological and pavement surface current conditions and trends, ADT, and available resources. The practice of deicing can begin once precipitation has reached the roadway, but may continue until after the weather event has ended, until a satisfactory pavement conditions are reached. Deicing usually will require more chemicals than anti-icing to produce the same LOS (61).

5.1.2.2 Anti-icing

Anti-icing is a proactive treatment method for snow and ice on roads, which can be initiated before the weather event begins or just as the precipitation begins falling (i.e. “just-in-time” anti-icing). Anti-icing can help to prevent black ice, and also prevents or weakens the bond that could form between the pavement and ice, ultimately allowing for easier removal of snow and ice using plowing techniques. Anti-icing can be done with liquid, solid, and pre-wet chemicals. Application rates for anti-icing are typically 3 to 5 times lower than those used in deicing (64).

Application rates for anti-icing reported in NCHRP Report 577 for liquid, solid, and pre-wet solids range from 65 to 400 lbs/l-m with a working temperature range of 10° to 32° F (-12° to 0° C) (61, 64, 65). These are general guidelines with application rates varying based on meteorological and pavement surface current conditions and trends, ADT, and available resources.

The use of anti-icing has been particularly successful as a liquid pretreatment for forecasted frost and icy locations, and can be used in most weather and traffic conditions and locations with a few exceptions. First, anti-icing with a liquid chemical is not a good strategy when the pavement temperatures are below the working temperature of the product at the onset of a snowfall event, or at any freezing pavement temperatures when the snowfall event is forecast to be followed by rain. Second, anti-icing with liquid chemicals is not recommended during freezing rain or sleet events (61).

In addition to these limitations, the effectiveness of anti-icing depends on the existence of several other elements. It is necessary for the agency to have accurate information regarding current and forecast pavement temperature conditions and current and forecast air temperature and humidity.

It is also necessary to have vehicle equipment that is suited to transporting and dispensing anti-icing chemicals at the proper amounts. Production and/or storage of anti-icing chemicals at a maintenance yard may require additional equipment as well.

5.1.2.3 Pre-Wetting

The method of pre-wetting involves spraying liquid deicing chemicals onto solid deicing chemicals or abrasives to increase their effectiveness and help them stick to the road (64). Adding liquid chemicals to solid chemicals reduces bounce and scatter and accelerates the formation of brine. Once this occurs, the material is more likely to stay on the roadway rather than be displaced by traffic. Applying liquid deicing chemical to abrasives adds weight and cushions the fall of the abrasives as they hit the roadway, and may help it stick to the road (see Section 5.1.1 on sanding).

5.1.3 Do Nothing

There is an option in winter road maintenance to "do nothing". This option would only be employed when air and pavement temperatures are extremely cold and new or blowing snow is cold and light, such that traffic and wind effectively remove the snow from the roadway (60). In this situation, applying chemicals or treated abrasives could lead to accumulation of snow and ice, creating more of a problem that must then be treated.

5.2 Weather Information in Support of Snow and Ice Control

As noted in the previous section, chemical methods of snow and ice control have a greater reliance on weather information than other methods. Therefore, one aspect of the survey of winter maintenance personnel focused on the use of different types of winter maintenance operations, including anti-icing, plowing/deicing, and sanding/grit application. The use of these maintenance strategies and the associated weather information by winter maintenance professionals are summarized in following sub-sections.

5.2.1 Methods Used for Winter Maintenance Operations

Figure 8 displays the current use of maintenance strategies from 88 respondents[4]. All of the respondents used plowing and deicing in their winter maintenance operations. Plowing and deicing were grouped together because they are reactive snow and ice control operations, initiated in response to winter precipitation events which have already occurred. Anti-icing and sanding/grit were also widely used, but the sanding/grit strategy had a lower percentage of use. In addition to these three strategies, around 40 percent of respondents also use many other strategies including (but not limited to) brush cutting, snow fence, and avalanche control.

[4] Not all survey respondents responded to this question.

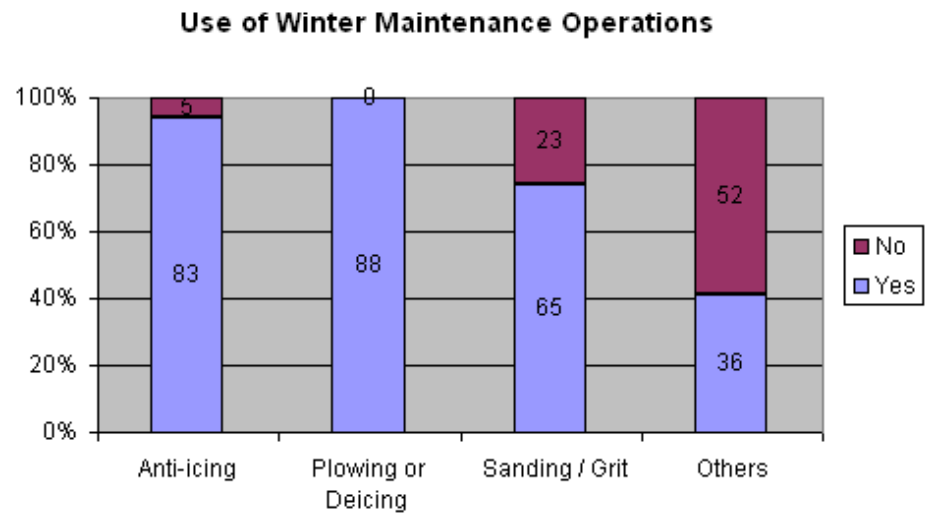


Figure 8: Current Use of Winter Maintenance Operations

Respondents were asked to assess how they anticipated the frequency of these different winter maintenance operations changing in the future. The results are shown in Figure 9. It can be observed that the majority of respondents said they would not change the amount of plowing, deicing and sanding/grit they would use in winter maintenance operations. Almost one-third of the respondents said they might use sanding/grit less frequently in the future. Unlike deicing, plowing and sanding/grit, 49 of respondents (56 percent) would like to use anti-icing more frequently. With only three respondents indicating that they would reduce the use of anti-icing in the future, it appears that there is a clear trend toward increased usage of anti-icing.

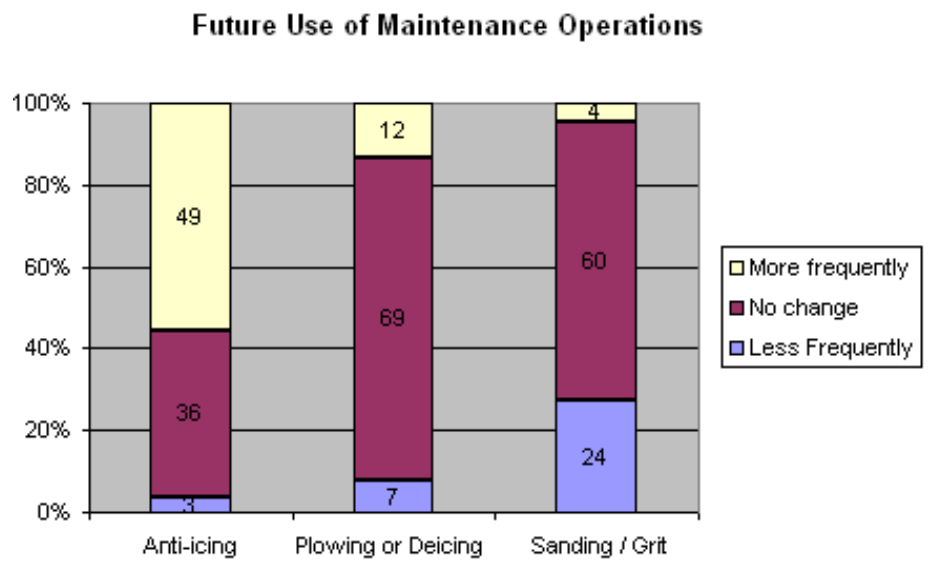


Figure 9: Future Use of Winter Maintenance Operations

5.2.2 Weather Data Used in Winter Maintenance Operations

The weather information needed to support winter maintenance activities differs from what may be necessary for other surface transportation applications, let alone other users. Winter maintenance operations focus on dispensing the right chemicals or materials at the right locations and the right time, in an effort to provide the desired level of service and improve safety and mobility in a cost-effective manner. The effectiveness of various chemicals and materials will, in turn, depend on various parameters associated with the current and forecast roadway environment.

Respondents were asked to identify which weather parameters are used, or would be used if available, to help in various types of snow and ice control operations. Table 19 and Table 20 present the types of current and forecast weather information that the survey respondents used or would like to use if available. In each table, the weather parameters that have been used by less than 60 percent of the respondents, or would be used if available by more than 10 percent of them are highlighted.

5.2.2.1 Current Weather Data

As shown in Table 19, the weather parameters used most frequently for anti-icing practices are pavement temperature and precipitation type. Other parameters used for anti-icing by 66 to 83 percent of the respondents include air temperature, pavement surface condition, precipitation rate, precipitation occurrence, wind speed and direction, and humidity/dew point. It is interesting to note that chemical concentration[5], solar radiation/cloud cover, and pressure are not widely used, but respondents suggested these parameters would be used more if they were available. Thus, the limited use of these parameters could have been caused, in part, by their non-availability.

The weather parameters most frequently used for plowing or deicing are precipitation rate or type. Other parameters used for plowing or deicing by 78 to 87 percent of respondents include precipitation occurrence, pavement surface condition, pavement temperature, air temperature, and wind speed and direction. Like anti-icing, chemical concentration, solar radiation/cloud cover, and pressure for plowing or deicing are not widely used, but would be used more if available.

[5] It should be noted that those people looking at RWIS-ESS data are also looking at chemical concentration, which is in the format of the eutectic point and they just don't know it.

Table 19: Use of Current Weather Information for Winter Maintenance Operations

Weather Parameters	Anti-Icing		Plowing or Deicing		Sanding / Grit	
	Use	Do not use, but would use if available	Use	Do not use, but would use if available	Use	Do not use, but would use if available
Pavement temperature	79 (90.8%)	6 (6.9%)	72 (81.8%)	8 (9.1%)	58 (66.7%)	7 (8.1%)
Pavement surface condition	71 (82.8%)	6 (6.9%)	74 (84.1%)	4 (4.6%)	57 (63.2%)	6 (6.9%)
Chemical concentration	52 (59.8%)	19 (21.8%)	52 (59.1%)	16 (18.2%)	24 (27.6%)	13 (14.9%)
Wind speed and direction	62 (71.3%)	6 (6.9%)	69 (78.4%)	5 (5.7%)	46 (52.9%)	6 (6.9%)
Air temperature	75 (86.2%)	3 (3.5%)	70 (79.6%)	3 (3.4%)	53 (60.9%)	3 (3.5%)
Dewpoint and humidity	58 (66.7%)	7 (8.1%)	39 (44.3%)	8 (9.1%)	25 (28.7%)	9 (10.3%)
Solar radiation/cloud cover	34 (39.1%)	17 (19.5%)	48 (54.6%)	10 (11.7%)	33 (37.9%)	8 (9.2%)
Pressure	21 (24.1%)	16 (18.4%)	21 (23.7%)	11 (12.5%)	15 (17.2%)	9 (10.3%)
Precipitation occurrence	67 (77.0%)	5 (5.8%)	77 (87.5%)	2 (2.3%)	49 (56.3%)	4 (4.6%)
Precipitation rate	71 (81.6%)	4 (4.6%)	83 (94.3%)	1 (1.1%)	56 (64.4%)	4 (4.6%)
Precipitation type	78 (90.8%)	2 (2.3%)	82 (93.2%)	1 (1.1%)	57 (65.5%)	5 (5.8%)
No. of Respondents	87		88		87	

Weather parameters used for sanding/grit application by at least 60 percent of the respondents include pavement temperature, precipitation type, precipitation rate, pavement surface condition, and air temperature (Table 19). Parameters used less than 30 percent of the time include dewpoint/ humidity, chemical concentration, and pressure.

In general, Table 19 shows that the precipitation rate and type and the pavement temperature and condition parameters are most widely used, and the parameters used the least would be used more if available. Further, it appears that increased use of anti-icing in winter maintenance operations will stimulate the demand for weather information. For instance, nearly 98 percent of respondents indicated that pavement temperature information is used or would be used to support anti-icing operations, compared to 90 percent and 75 percent of respondents for plowing/deicing and sanding/grit, respectively. In other words, while pavement temperature is valued for all winter maintenance operations, it becomes essentially mandatory to support anti-icing. There would also be greater dependence on air temperature and dewpoint/humidity information as the use of anti-icing increases.

A higher percentage of respondents reported using information on wind speed and direction to support plowing/deicing operations than for supporting either anti-icing or sanding/grit operations. This may be because wind could contribute to snowdrifts that would reduce the effectiveness of plowing, and wind could also cause uneven dispersion of deicing chemicals. Precipitation rate also appeared to be more important in plowing/deicing operations, since heavier precipitation rates may mean plowing is the only feasible snow control option and/or may dilute the effectiveness of deicing agents. In general, however, respondents indicated that plowing/deicing operations required a similar suite of weather information parameters as anti-icing. Sanding/grit operations appear to generally require less weather information than other snow and ice control operations; however, as noted in Figure 9, this type of operation may decrease in the future in favor of other treatment methods.

5.2.2.2 Weather Data from Forecasts

Table 20 summarizes the forecast weather parameters which respondents indicated were most helpful in supporting different winter maintenance operations. Forecast parameters used most widely for anti-icing practices include precipitation begin/end time and precipitation type. Precipitation amount, pavement temperature trends, and pavement surface condition are also used by at least 75 percent of respondents in anti-icing operations. As was found when examining weather parameters related to current conditions, chemical concentration and solar radiation/cloud cover were not used as frequently as were other parameters. In addition to these, barometric pressure was listed as a parameter not used frequently by respondents, but which respondents said they would use if they were available.

The forecast parameters used most frequently to support plowing or deicing include precipitation type, begin/end time, and amount. Chemical concentration, solar radiation/cloud cover, pressure, and dew point/humidity were not reported to be used as frequently. The forecast parameters used most frequently for sanding/grit include precipitation type, precipitation begin/end time, and pavement surface condition.

In general, respondents reported slightly lesser reliance on forecast weather parameters than on information on current conditions. Similar to what was observed with current weather parameters, a horizontal comparison finds that the respondents using sanding/grit used less weather information than those employing anti-icing and plowing or deicing. In all types of operations, pressure (either current or forecast) information had the smallest percentage of use by the respondents. In addition, precipitation begin/end time and precipitation type were the most widely used forecast weather information. Based on the weather information respondents said that they do or would use, the trend toward increased use of anti-icing will result in increasing reliance on forecasts for pavement temperature trends and dewpoint/humidity.

Table 20: Use of Forecast Weather Information for Winter Maintenance Operations

Weather Parameters	Anti-Icing		Plowing or Deicing		Sanding / Grit	
	Use	Do not use, but would use if available	Use	Do not use, but would use if available	Use	Do not use, but would use if available
Pavement temperature Trends	68 (78.2%)	10 (11.5%)	64 (72.7%)	9 (10.2%)	51 (58.6%)	7 (8.1%)
Pavement surface condition	68 (78.2%)	6 (6.9%)	66 (75.0%)	6 (6.8%)	53 (60.9%)	7 (8.1%)
Chemical concentration	45 (51.7%)	17 (19.5%)	48 (54.6%)	17 (19.3%)	28 (32.2%)	12 (13.8%)
Wind speed and direction	62 (71.3%)	5 (5.8%)	65 (73.9%)	4 (4.6%)	46 (52.9%)	5 (5.8%)
Air temperature trends	61 (70.1%)	8 (9.2%)	65 (73.9%)	6 (6.8%)	46 (52.9%)	4 (4.6%)
Dewpoint and humidity	55 (63.2%)	6 (6.9%)	40 (45.5%)	6 (6.8%)	21 (24.1%)	8 (9.2%)
Solar radiation/cloud cover	29 (33.3%)	16 (18.4%)	48 (54.6%)	10 (11.4%)	29 (33.3%)	8 (9.2%)
Pressure	22 (25.3%)	14 (16.1%)	23 (26.1%)	11 (11.4%)	13 (14.9%)	9 (10.3%)
Precipitation amount	71 (81.6%)	3 (3.5%)	79 (89.8%)	1 (1.1%)	52 (59.8%)	3 (3.5%)
Precipitation begin/end time	76 (87.4%)	4 (4.6%)	80 (90.9%)	1 (1.1%)	53 (60.9%)	3 (3.5%)
Precipitation type	76 (87.4%)	4 (4.6%)	81 (92.1%)	1 (2.3%)	55 (63.2%)	3 (3.5%)
No. of Respondents	87		88		87	

5.3 Summary

This chapter synthesized information gathered from a literature review, and surveys of winter maintenance personnel to characterize how weather information may be used to support snow and ice control operations.

This chapter reviewed three primary types of snow and ice control strategies: mechanical methods (i.e., plowing, brooming, blowing, applying abrasives), chemical methods (i.e., deicing, anti-icing, pre-wetting), and "do-nothing." The method of treatment depends on many factors such as weather conditions, the options available to the agency, event timing, site-specific factors, and the prescribed LOS employed by that agency. Survey results revealed that plowing, deicing, and anti-icing were widely used by survey respondents, and that the usage of anti-icing is anticipated to increase in the future. Weather information is important in supporting a variety of winter maintenance operations; however, respondents reported needing more weather information to support anti-icing and plowing/de-icing than to support sanding/grit operations.

Together, these findings suggest that the demand for weather information among winter maintenance personnel will increase in the future.

Survey results showed that maintenance personnel relied less on forecast weather parameters than information on current conditions. Current road and weather parameters of interest included pavement temperature, air temperature, pavement surface condition, precipitation rate, precipitation occurrence, wind speed and direction, and humidity/dew point. Forecast road and weather parameters of interest included the onset/end time of precipitation, precipitation type and amount, pavement temperature trends, and pavement surface condition.

These findings have important implications for the type of weather information that would be most beneficial to winter maintenance personnel. Traditional weather data sources usually focus on atmospheric meteorological conditions, but not on the pavement surface. Moreover, since conditions on the pavement surface may be very different from atmospheric conditions, traditional weather sources are likely not adequate to meet the needs of snow and ice control operations like anti-icing. With increased usage of anti-icing expected in the future, it will be even more important for transportation agencies to secure information on pavement temperature (current and forecast) and pavement surface conditions. This information is typically not available through free information sources, and is even less likely to be tailored to the roadway environment. Investments in improved weather information sources, whether in private-sector weather forecast providers, RWIS-ESS or decision support systems, are necessary to support snow and ice control operations as they are currently conducted.

CHAPTER 6. WEATHER USE BENEFIT—COST ANALYSIS

The previous chapters reviewed and documented what weather sources may be useful for winter maintenance, what strategies are currently used for snow and ice control, and how weather information is used to support winter maintenance operations. As described in CHAPTER 5, free weather sources (i.e., National Weather Service (NWS)) are not typically designed for the roadway environment, and investments are necessary to obtain targeted weather information from other sources (e.g., private-sector weather forecast providers, RWIS, DSS). Thus, it is important to decide whether the investments are worthwhile. The objective of this chapter is to analyze the benefits and costs associated with the use of weather information in winter maintenance. This chapter focuses on tangible benefits and costs; the secondary (intangible) benefits of RWIS will be investigated and provided in the next chapter.

This chapter first describes the model of winter maintenance costs. A model that includes several explanatory variables (e.g., maintenance lane miles, weather use) is established for cost estimation. Based on the model, a methodology consisting of Artificial Neural Network (ANN) and sensitivity analysis methods is proposed to estimate the benefits associated with weather information. The methods are then applied to case studies for three states (Iowa, Nevada, and Michigan) to investigate the tangible benefits and costs. Key findings from the case studies are finally summarized.

6.1 Winter Maintenance Cost Model

Winter maintenance costs refer to direct costs of materials, labor, and equipment. Indirect costs (e.g., societal costs) are excluded as they are difficult to quantify. The usage of materials, labor, and equipment can be affected by many factors; these factors are shown symbolically in Equation 1. The cost model is established at the maintenance unit (e.g., maintenance shed, maintenance garage, cost center, patrol yard) level, and the total winter maintenance costs are the sum of costs over all maintenance units within the state.

$$WMC_k = f(LM_k, LOS_k, WSI_k, WI_k, AI_k) \tag{1}$$

where

WMC_k = winter maintenance cost for the kth maintenance unit per winter season
LM_k = lane miles of roadway maintained by the maintenance unit
LOS_k = level of service of the roadways maintained by the maintenance unit, often characterized by the pavement condition
WSI_k = winter severity index for the area managed by the maintenance unit
WI_k= weather information usage (frequency and accuracy) by the maintenance unit
AI_k = level of anti-icing used by the maintenance unit

Each maintenance unit is responsible for one or more route segments. Considering that roadways are classified into different service levels (often characterized by the daily traffic volume, assuming j levels), LM is then a $1\times j$ vector to indicate lane miles of each level, as shown in

Equation 2. The lane mile of a route segment is the product of the segment length and the number of lanes.

$$LM_k = [\sum_1^k L_{1m} \times Ln_{1m}, ..., \sum_1^k L_{jm} \times Ln_{jm}] \quad (2)$$

where L_m is the length of the *m*th roadway segment and Ln_m represents the number of lanes on this segment. In the previous Utah UDOT study (29), a *VMT* factor (vehicle miles traveled on the winter roadways maintained by a maintenance unit) was used. The calculation of *VMT* is based on Annual Average Daily Traffic (AADT) and length of highway segment. It is obvious that different service levels of highways have different levels of AADT and require different levels of maintenance, but the *LM* factor is more directly related to winter maintenance costs than *VMT*. This is because *VMT* is a contributing factor to maintenance but *LM* is the result of maintenance. However, in the case that *LM* information is not available, *VMT* can be used instead.

LOS refers to the actual pavement condition with respect to accumulation of liquid or frozen precipitate. The calculation of *LOS* may vary from state to state. For example, in some states, *LOS* is the number of hours until near normal pavement condition is restored. In other states, *LOS* represents the number of reports for various maintenance conditions (referred to *LOM*—level of maintenance in 29).

The severity of winter weather affects winter road maintenance. Obviously, winter weather severity varies from place to place. Currently, several indices may be used to measure winter weather severity (66). A commonly used *WSI* is the index proposed in the Strategic Highway Research Program (SHRP) study (6). This index is calculated based on the mean daily snowfall, and minimum and maximum temperatures averaged over the season. In addition, as will be described later in the case study, some states have developed their own indices for winter maintenance.

WI refers to the degree to which a maintenance unit uses weather information. *WI* has two meanings for winter maintenance: one is the frequency of using weather information (observations and forecasts), and the other is the accuracy of weather information. Thus, *WI* can be a 1×2 vector indicating frequency and accuracy.

Anti-icing is a proactive treatment method for snow and ice on roads that can be initiated before the weather event begins or just as the precipitation begins falling (i.e., "just-in-time" anti-icing). The use of anti-icing can affect winter maintenance costs. A study found that the application rates for anti-icing are typically three to five times lower than those used in deicing (67).

In addition to the input variables in Equation 1, other factors may also affect winter maintenance costs and need be added into the model if possible. Whatever variables are included in the model, it is necessary to identify the key factors that contribute to winter maintenance costs, as will be discussed in the following sections.

6.2 Methodology

The previously outlined cost model can provide a good framework to evaluate the effects of weather information in winter maintenance costs. Before the evaluation using the cost model, it is important to identify the factors/variables that have significant impacts on winter maintenance costs. Hence, a two-step research methodology is developed. In the first stage, a sensitivity analysis method is used to explore the effects of various input variables on the output (cost) based on trained networks (by using the neural network method). This stage will determine what inputs should be included in the cost model. Those input variables that have negligible impacts will be removed from analysis. In the second stage, a neural network is used to model winter maintenance costs and evaluate the impacts of weather information, given that the weather information factor is not excluded in the first stage. Both the neural network and sensitivity analysis methods are introduced as follows.

6.2.1 Neural Networks

A neural network is a modeling technique to mimic the performance of a system based on observed behavior of neurons. Neural networks are in the borderline area of artificial intelligence and approximation algorithms. As shown in Figure 10, a widely used neural network consists of three layers: the input layer, the hidden layer and the output layer. Neural network modeling is a dynamic and complex process that requires the determination of the internal structure and rules such as the number of hidden layers and neurons.

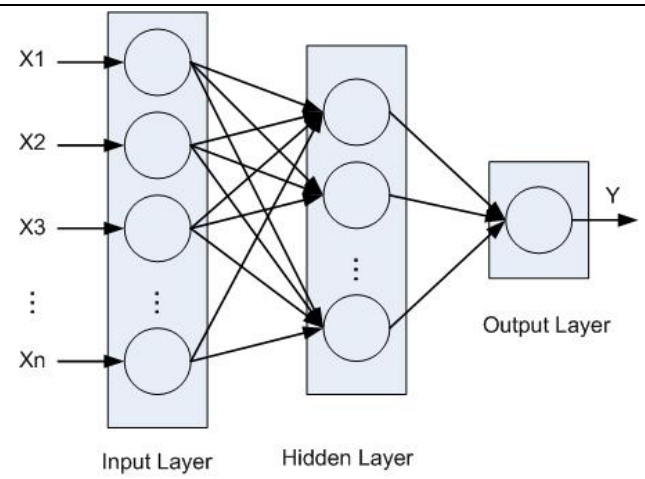


Figure 10: Architecture of the neural network model with one hidden layer

To date, there are numerous types of neural networks using different algorithms. Among them, the Back-propagation Neural Network (BPNN) is the most popular network because of its simplicity and effectiveness (68). The BPNN accepts inputs at the input layer and the inputs are summed with weights and passed to the hidden layer. Then, the sums in the hidden layer are weighted and passed to the output layer to generate the output. The back-propagation algorithm develops the input-to-output mapping by minimizing a Mean Square Error (MSE) function:

$$MSE = \frac{\sqrt{\sum_{i=1}^{n}(y_i - E(i))^2}}{n} \tag{3}$$

where n is the sample size of the training dataset, y_i is the model output (e.g., winter maintenance cost) related to the sample $i(i = 1,...,n)$, and $E(i)$ is the estimated output.

6.2.2 Sensitivity Analysis

Sensitivity analysis is a method to study, qualitatively or quantitatively, how the uncertainty in the model output is attributed to different sources of variation (69). In this study, the objective of sensitivity analysis is to find the subset of input variables that are most responsible for variation in model output. In real-world applications, it is common that the sample size for network training is limited and the dataset includes many input variables, which may present challenges for appropriate training. Hence, it is important to reduce the number of inputs in the network model since some of the inputs may have negligible impacts (very low sensitivities), which in turn reduces the complexity of network and training time.

Before conducting sensitivity analysis, preparations need to be made. First, the input and output data are normalized. Normalization of data means that the parameters are scaled equally so that the sensitivities of input variables can be compared. Second, data from all normalized input variables are used to train the network. Sensitivity analysis is conducted based on the trained network.

To normalize the dataset, a minimum–maximum method was used. The min–max normalization preprocesses the network training set by normalizing the inputs and outputs so that they fall in the interval [-1, 1]. Through normalization, the input parameters are scaled equally. The min–max normalization can be realized through the following equation:

$$Pn = 2 \times (P - MinP \times OneQ)./((MaxP - MinP) \times OneQ) - 1 \tag{4}$$

where

P	= a $R \times Q$ matrix of input (or output) vectors
$MinP$	= a $R \times 1$ vector containing minimums for each P
$MaxP$	= a $R \times 1$ vector containing maximums for each P
$OneQ$	= a $1 \times Q$ vector containing 1s
Pn	= a $R \times Q$ matrix of normalized input (or output) vectors

It should be noted that in the normalization, a system (i.e., cost model in this study) is assumed: $y = f(x_1, x_2, ..., x_n)$, where y is the output (or result) and $x_1, x_2, ...x_n$ denotes the inputs of the system.

Once the network is properly trained, sensitivity analysis can be realized through the following steps:

1) Estimate mean and standard deviation for each variable $x_i (i = 1, 2, ..., n)$.
2) For x_1, evenly divide the interval $[\overline{x}_1 - \sigma(x_1), \overline{x}_1 + \sigma(x_1)]$ (σ is the standard deviation) into *k* sub-intervals. Thus, there are *k+1* input values $x_1^1, x_1^2, ..., x_1^{k+1}$. This study uses *k=100*, which means that the length of each interval (Δx_i) is less than $2/100 = 0.02$. One should be aware of the possibilities that $\overline{x}_1 - \sigma(x_1) < -1$ and $\overline{x}_1 + \sigma(x_1) > 1$, under which the input values outside the range of [-1, 1] will be excluded.
3) Calculate the results ($y_1^1, y_1^2, ..., y_1^{k+1}$) of the system for each element of the sample; other inputs are fixed at their respective means.
4) Analyze sensitivity of x_1 by using partial derivatives: $S_1 = \partial y_1 / \partial x_1$, which is a $1 \times k$ vector. The calculation of sensitivity is approximated by the first order of the Taylor series (70):

$$S_1^i = \frac{\partial y_1^i}{\partial x_1^i} \approx \frac{y_1^i(x_i + \Delta x_i) - y_1^i(x_i)}{\Delta x_i} \text{ for each } i = 1, 2, ..., k+1 \tag{5}$$

where S_1^i is the sensitivity of x_1^i.

5) Calculate the average sensitivity (which is a positive value) for x_1: $S_1 = \left| \frac{1}{k} \sum_{i=1}^{k} S_1^i \right|$
6) Repeat steps 1 through 4 for the rest of the input variables.
7) Obtain $S_1, S_2, ..., S_n$ for all input variables. Normalize the sensitivity values so that $\sum_{j=1}^{n} \hat{S}_j = 1$, where $\hat{S}_j = S_j / \sum S$. The final sensitivity values are $\hat{S}_1, \hat{S}_2, ..., \hat{S}_n$. These values can then be used to analyze their relative importance in the output variable, and to select key factors for the system.

6.3 Iowa Case Study

6.3.1 Study Data

To develop the cost model (Equation 1), winter maintenance data during the winter season of 2006–07 were gathered from Iowa DOT. The maintenance unit in this state is referred to as a "cost center." Each cost center was responsible for different route segments, which are classified into four service levels: A (the highest level), B, C, and D.

The dataset included winter maintenance cost, lane miles, and winter weather severity index for each cost center. Winter maintenance cost consisted of material, labor, and equipment costs. The total cost was used as the output variable (*WMC*) of the cost model. The lane miles maintained by each cost center were available at the service level of roadway. During this winter season, service level D was merged into level C. Thus, the lane miles factor includes three variables, *LM_A* (lane miles of service level A routes), *LM_B* (lane miles of service level B routes), and

LM_C (lane miles of service level C routes). A total of approximately 24,500 lane miles of roadways were maintained during this winter season.

The Iowa DOT developed a winter weather severity index for winter maintenance, which is named "New Wisconsin Index Three" (71). This index creates a higher score for locations that report longer events, more frequent events, and more snowfall. The duration and frequency of the different events are normalized by the Iowa expected extreme for each event, then scaled by an "importance" factor. Generally, the colder the lowest pavement temperatures during an event are, the higher the index score. High indices correlate to more severe winters. The index is calculated based on the number of wet snow events, dry snow events, and freezing rain events; snowfall in inches; the number of hours of wet snow, dry snow, mixed precipitation, freezing rain, blowing snow, and sleet; and pavement temperatures during precipitation events.

To develop the *LOS* variable in Equation 1, the number of hours until near normal pavement condition during each (maintenance) event was computed. The number of hours that a roadway segment operated under unacceptable pavement condition was calculated over the winter season. It was found that the *LOS* values for different service levels of routes were close to one another within a cost center. Hence, to reduce the number of input variables in the cost model, the mean value of the numbers was used to indicate *LOS*.

Iowa DOT maintenance personnel were surveyed to investigate the use of weather information and the level of anti-icing for winter maintenance. The survey asked about the frequency that weather information was received from various sources (e.g., roadside weather stations for weather observations, private-sector weather forecast providers), the accuracy of weather observations and forecasts compared to free weather services (e.g., NWS), the level of anti-icing, etc. The questionnaire and survey results are presented in Appendices A and B. Numerical scales were used to indicate qualitative data of frequency (1 ~ 4), accuracy (1 ~ 5), and level of anti-icing (1 ~ 5), as illustrated in Table 21.

The survey was conducted for the winter season of 2007–08; however, Iowa DOT indicated that the use of weather information as well as the anti-icing level during this season was similar to that of 2006–07. Thus, it is assumed that both the use of weather information and the level of anti-icing in a cost center did not change between these two winter seasons.

The survey revealed that maintenance personnel in the state used most weather forecasts from two private sectors—Meridian and Meteorlogix/DTN. Hence, the frequency and accuracy from these two providers were averaged for each cost center. Then the frequency and accuracy values of weather observations and weather forecasts were averaged to obtain the overall weather use information.

Table 21: Numerical Scales of Weather Information and Level of Anti-Icing

Values	Denotation of Numeric values		
	Frequency	Accuracy	Anti-Icing
1	Never	Much less accurate than free weather services (e.g., NWS)	Never
2	Less than daily, and only when storms are forecast or occurring	Less accurate	Interested in anti-icing but don't have the right equipment and/or chemical
3	Daily	Same	Interested in anti-icing but don't have good enough forecasts
4	More than once per day (more frequent when storms are forecast or occurring)	More accurate	Regularly employ anti-icing on selected routes
5	N/A	Much more accurate	Regularly employ anti-icing on all eligible routes

Eight variables are used as preliminary inputs to the cost model, which in this case is revised to the following equation.

$$WMC_k = f(LM\_A_k, LM\_B_k, LM\_C_k, LOS_k, WSI_k, WI\_F_k, WI\_A_k, AI_k) \quad (6)$$

where

LM_A_k = lane miles of service level A routes maintained by the *k*th cost center
LM_B_k = lane miles of service level B routes
LM_C_k = lane miles of service level C routes
LOS_k = the number of hours under unacceptable pavement conditions
WSI_k = winter weather severity index
WI_F_k = the frequency of using weather information
WI_A_k = the accuracy of weather information
AI_k = the level of anti-icing

Equation 6 defines minimum data requirements for a cost center to be eligible for the study; in all, 82 cost centers met the requirements. Table 22 statistically describes input and output variables in the (original) dataset.

Table 22: Statistical Descriptions of Variables (Iowa)

Variables	Mean	Standard Deviation	Coefficient of Variation
LM_A (mile)	44	68	155%
LM_B (mile)	107	84	79%
LM_C (mile)	84	52	62%
LOS (hour)	362	107	30%
WSI	16.52	4.09	25%
WI_F	2.75	0.46	17%
WI_A	3.63	0.51	14%
AI	4.25	0.99	23%
WMC ($)	178,483	91,287	51%

6.3.2 Identification of Key Input Variables

As discussed earlier, sensitivity analysis can be conducted to decide the input variables to be used for the modeling of neural networks. To this end, the original dataset was first normalized. The whole normalized dataset was used for network training. The network consisted of an input layer with eight input variables, a hidden layer with four nodes, and an output layer with one output variable. As will be shown later, the network had good training results with the simple network design. The network was trained for several times with 1,000 epochs (number of steps in the training process). The *MSE* in Equation 3 was used for evaluating the performance of the model. The *MSE* values are displayed in Figure 11 for six runs. The final *MSE* values were very low in these runs. It was found that 1,000 epochs was adequate for network training because the improvement in *MSE* was minimal beyond that number. Using larger numbers of epochs may result in overtraining—the network memorizes the noise in the training set and loses its ability to generalize new data.

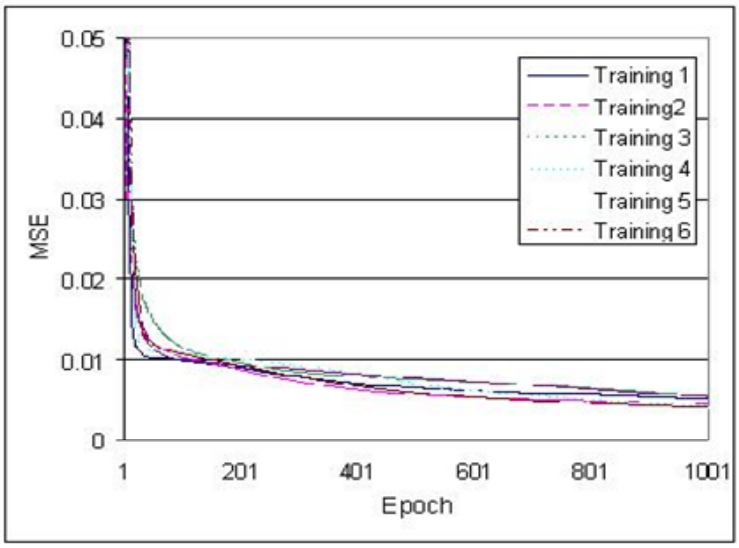


Figure 11: Learning Curves (Iowa)

Sensitivity analysis was conducted for each of the six runs. The analysis results are shown in Figure 12, in which the sensitivity values are the means of the six runs. Obviously, the lane miles factors, especially *LM_A* and *LM_B*, had high sensitivities to winter maintenance costs. The sum of sensitivity values of lane mile variables is about 0.73. The other five variables had similar sensitivities to the costs and were varying around 0.05. Given that even 1 percent of winter maintenance costs is substantial, it is recommended that all variables be included in the modeling of winter maintenance costs.

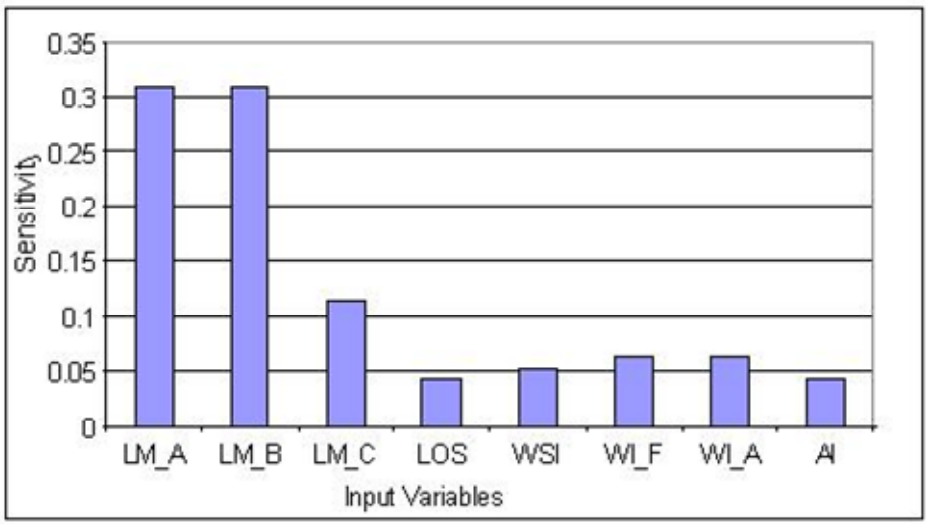


Figure 12: Sensitivity Analysis for Input Variables (Iowa)

6.3.3 Impacts of Weather Information on Costs

With the identification of input variables, the original dataset was divided into two parts: a training dataset and a testing dataset. To do this, the dataset (82 samples) was first randomized, and then one sample was selected for every ten samples. Thus, the training and testing datasets included 73 and 9 samples, respectively. The same network configuration in the sensitivity analysis was used for training. Figure 13 shows that the network had good training and testing results. The R^2 (regression coefficient) value of the training dataset was 0.93.

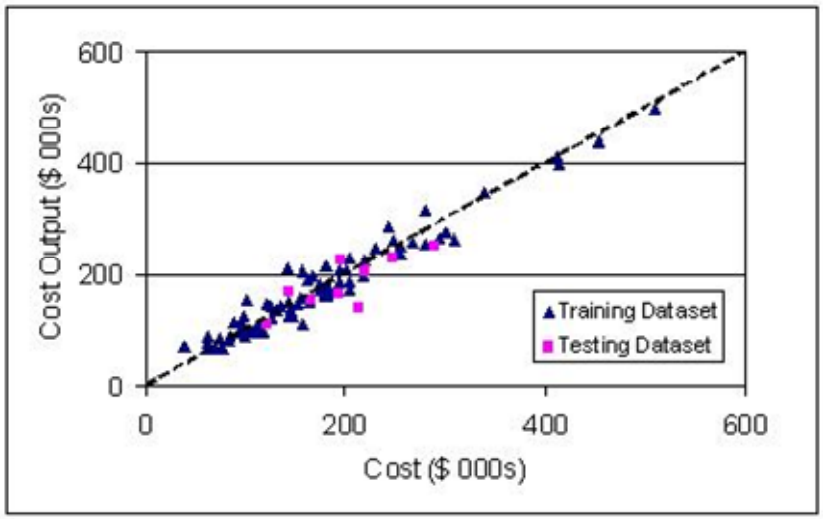


Figure 13: Results of Network Training and Testing (Iowa)

To evaluate the impacts of weather information (*WI_F* and *WI_A*) on winter maintenance costs, analysis was conducted similar to the sensitivity analysis, but only included steps 1, 2, and 3. Other variables were fixed at their respective means. The analysis results of *WI_F* and *WI_A* are shown in Figure 14. It was found that the mean cost decreased with the increase frequency or accuracy. Moreover, the slopes of the frequency curve became flatter with the increase of frequency, while those of the accuracy curve seemed to be fixed and displayed a linear relationship.

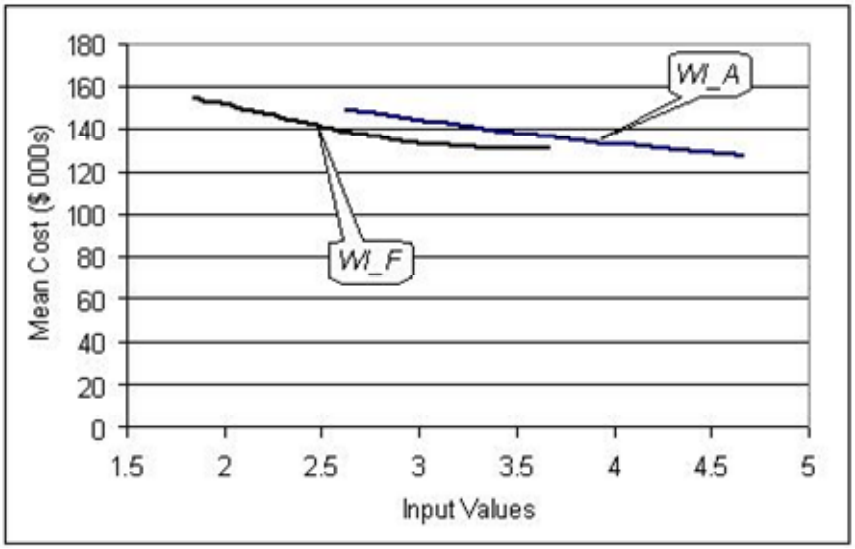


Figure 14: Impacts of Weather Information on Costs (Iowa)

Benefit–cost analysis can be used to quantify the effects of using weather information on the state's winter maintenance costs. It is an evaluation of the economic benefits and costs of a set of investment alternatives. To achieve this, three scenarios were developed as described as follows and displayed in Figure 15.

- The *base case* assumes that the state does not purchase weather observations and forecasts for winter maintenance. This case does not mean that winter maintenance personnel will not use any weather information; they will likely access free weather services (e.g., TV, newspapers, radio). Under this case, it is assumed that all cost centers have the same frequency of using weather information, and is equal to 2 (less than daily, and only when storms are forecast or occurring) in Table 1; also, the accuracy of weather information is 3 with free weather service.
- *Alternative 1* assumes that all cost centers are using weather information at their respective frequencies and accuracies. This represents real-world winter maintenance operations during the winter season of 2006–07.
- *Alternative 2* assumes that all cost centers are using weather information at their respect accuracy values, but all of them increase or keep their frequencies of using weather information to 4: more than once per day (more frequent when storms are forecast or occurring). This is to investigate the potential benefits of using more weather information under current accuracies.

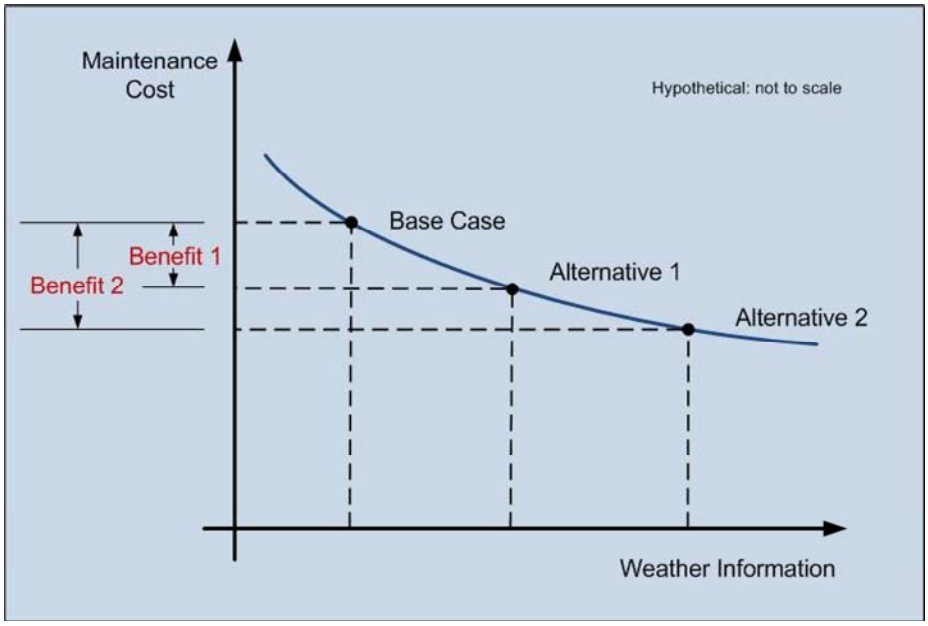


Figure 15: Base Case and Alternatives

During the analysis, the values of the variables other than frequency and accuracy were kept the same as in the original dataset. The frequency and accuracy values were changed according to different scenarios. The results of benefit–cost analysis are presented in Table 3. The benefits were calculated for the winter season of 2006–07, while costs were yearly based. The weather information costs include the following items:

- Maintenance contract: $130,000/year. This cost includes the replacement of parts of road weather sensors, travel, software support, and labor costs.
- Private-sector weather forecast services provided by Meteorlogix/DTN and Meridian: $298,000/year.
- Other costs: $20,000. This cost was used to cover non-warranty issues such as vandalism, damage from animals, and accidental damage.

Table 23 shows that the benefits of using weather information by Iowa DOT outweigh the costs, with a benefit–cost ratio of 1.8. It was also found that given existing weather information accuracy, increasing the frequency of using weather information can bring more benefits to winter maintenance. The benefits of Alternative 2 over Alternative 1 are about $281,000, or in other words the benefits can be furthered increased by thirty-four percent.

The benefit–cost analysis tends to be conservative because the benefits were calculated for only the 82 maintenance units in the dataset. More benefits are expected when applying this evaluation method to all maintenance units in the state.

Table 23: Benefit–Cost Analysis (Iowa)

Scenarios	Cost ($ 000s)	Benefits ($ 000s)	Weather Information Costs ($ 000s)	Benefit–cost Ratio
Base	15,448	N/A	N/A	N/A
Alternative 1	14,634	814	448	1.8
Alternative 2	14,353	1,095	N/A	N/A

6.4 Nevada Case Study

6.4.1 Study Data

Winter maintenance records during the winter season of 2006–2007 were obtained from Nevada DOT. Each maintenance record includes information of maintenance crew number, date of event, task description, maintenance route, mile posts, number of lanes, cause of maintenance, and costs (material, labor, and equipment use). Approximately 60 crews were involved in winter maintenance operations on 180 routes during this season. The total winter maintenance cost for each crew was calculated by summing up the costs of material, labor, and equipment use. The number of lane miles maintained by each crew can be also obtained by using the information of mile posts and number of lanes, and can be calculated by:

$$LM_k = \sum_{i=1}^{n} [MP\_to_{ik} - MP\_from_{ik}] * Ln_{ik} \tag{7}$$

where MP_to_{ik} = mile post number of the end of the *i*th maintenance for crew number k

MP_from_{ik} = mile post number of the beginning of the *i*th maintenance event

Ln_{ik} = number of lanes on this highway segment

Weather information (daily surface data) was collected from the National Climatic Data Center (NCDC). The data recorded precipitation, maximum and minimum temperature, snow depth, wind speed and direction, visibility, and dew point information. Hundreds of weather stations were installed in the state of Nevada, but data from the majority of the stations were not available for downloads. Moreover, some of them only provided weather data from the 1950s and 1960s, which was not practical for the calculation of *WSI* since climate characteristics may have changed in the last decades. Finally, some stations did not have enough data records. For these reasons, 11 weather stations were chosen to provide the daily records used to calculate *WSI*. The *WSI* was calculated by the method developed in the SHRP study (6). The *WSI* is expressed as:

$$WSI = a\sqrt{TI} + b\ln(\frac{S}{10}+1) + c\sqrt{\frac{N}{R+10}} + d \tag{8}$$

where:

TI is the temperature index: *TI*=0 if the minimum air temperature is above 32^0F (^{0}C); *TI*=1 if the maximum air temperature is above 32^0F, while the minimum air temperature is at or below 32^0F (^{0}C); *TI*=2 if the maximum air temperature is at or below 32^0F (^{0}C). The average daily value is used.

S represents snowfall: mean daily values in millimeters.

N is the number of air frosts: mean daily values of number of days with minimum air temperature at or below 32^0F (^{0}C) ($1 \le N \le 1$).

R is the temperature range: the value of mean monthly maximum air temperature minus mean monthly minimum air temperature in ^{0}C.

a, *b*, *c*, and *d* are coefficients. In this case, $a = -25.58, b = -35.68, c = -99.5, d = 50.0$ are used as developed in the SHRP study (6).

The *WSI* has a range from -50 (most severe weather and maximum level of snow and ice control), through 0 (not too severe weather and mean level of snow and ice), to 50 (warm weather and no need of snow and ice control).

The latitude, longitude, and elevation information of each weather station were also gathered. A linear regression analysis was conducted to investigate the relationship between *WSI* and those variables (latitude, longitude, and elevation). It was found that latitude and longitude significantly affected *WSI*, while the elevation variable did not at a 95 percent confidence level. The regression analysis also showed a strong relationship between *WSI* and the explanatory variables with an R-square value of 0.95. To calculate *WSI* for maintenance crews, latitude and longitude data of these crews were used and applied to the equation that was developed from the regression analysis.

The questionnaire in Appendix D was used to obtain weather use information in winter maintenance units. Phone interviews were conducted for this purpose. A total of 35 station supervisors were interviewed. Information about the frequency of using weather information, accuracy of weather information, and level of anti-icing for each maintenance crew was calculated in the same way as the Iowa case study. The detailed results of phone interviews are presented in the report of Technical Memorandum 3—Weather Use Benefit-Cost Analysis (72). It is noted that Northwest Weathernet services were widely used in Nevada for winter maintenance, while the use of RWIS was not, due in part to failure of RWIS, communication issues, and other technical problems.

The number of hours that pavements were under unacceptable conditions is not available for this case. Hence, the *LOS* variable in Equation 1 wasn't included in the benefit–cost analysis. Finally, five variables, including *LM*, *WSI*, *WI_F*, *WI_A*, and *AI*, were used for modeling winter maintenance costs, as shown in the following equation.

$$WMC_k = f(LM_k, WSI_k, WI\_F_k, WI\_A_k, AI_k) \quad (9)$$

The statistical descriptions of these variables are presented in Table 24. The coefficient of variation of *WSI* is a negative value and thus not presented.

Table 24: Statistical Descriptions of Variables (Nevada)

Variables	Mean	Standard Deviation	Coefficient of Variation (%)
LM (mile)	23666	18,136	77
WSI	-8.0	7.7	-
WI_F	3.49	0.59	17
WI_A	3.60	0.71	21
AI	3.72	1.59	43
WMC ($)	263,065	184,710	70

6.4.2 Sensitivity Analysis

Similar to the Iowa case study, the original dataset including all input and output variables were first normalized. The normalized dataset was further used for network training, and the trained network consisted of an input layer with five input variables, a hidden layer with four nodes, and an output layer with one output variable. Six runs were conducted to examine the MSEs of training. As shown in Figure 16, 50 epochs were enough for the training of this dataset to avoid overtraining.

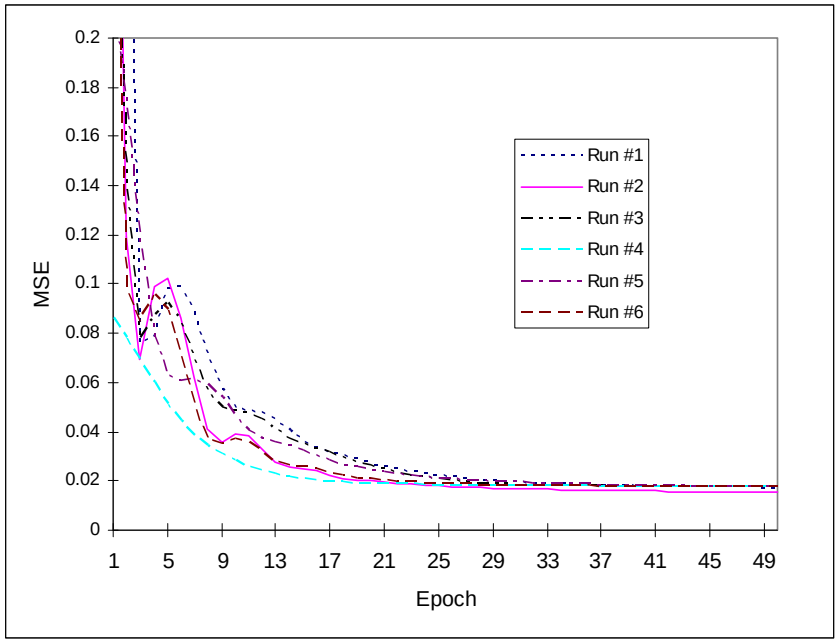


Figure 16: Learning Curves (Nevada)

Sensitivity analysis was conducted for each of the six runs (trainings). The analysis results are shown in Figure 17, in which the sensitivity values were the means of the six trainings. Winter maintenance costs (WMC) were highly sensitive to variations of *LM* and *WSI*; the sensitivity values for *WI_F*, *WI_A*, and *AI* were 0.02, 0.07, and 0.03, respectively. Based on the analysis results, all of these five variables were included in the further modeling of winter maintenance costs.

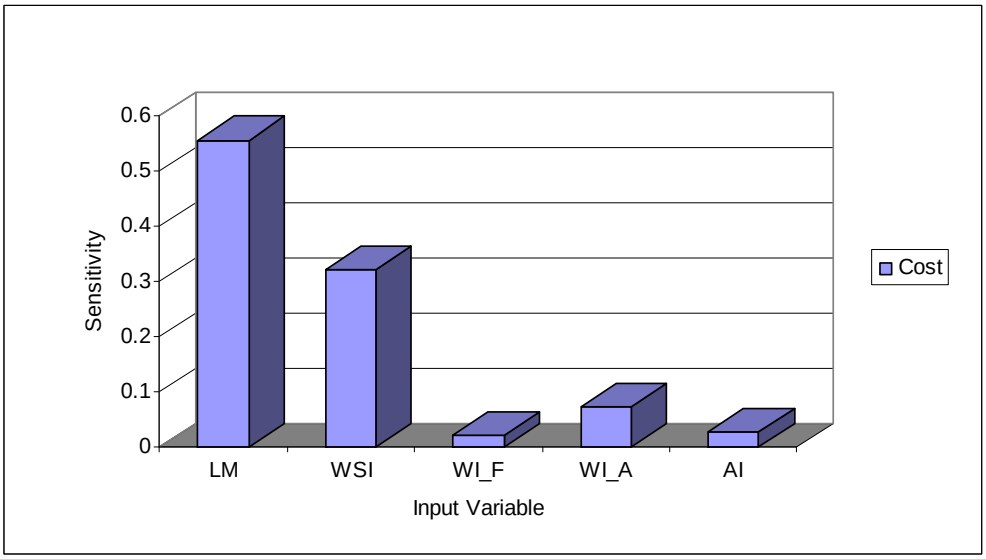


Figure 17: Sensitivity Analysis for Input Variables (Nevada)

6.4.3 Impacts of Weather Information on Costs

The original dataset with 34 samples was divided into a training dataset (30 samples) and a testing dataset (4 samples). The same network configuration in the sensitivity analysis was used for trainings with 50 epochs. Training results are shown in Figure 18. The R^2 (regression coefficient) value of the training dataset was 0.80. The results showed a relatively strong relationship between the actual and estimated costs.

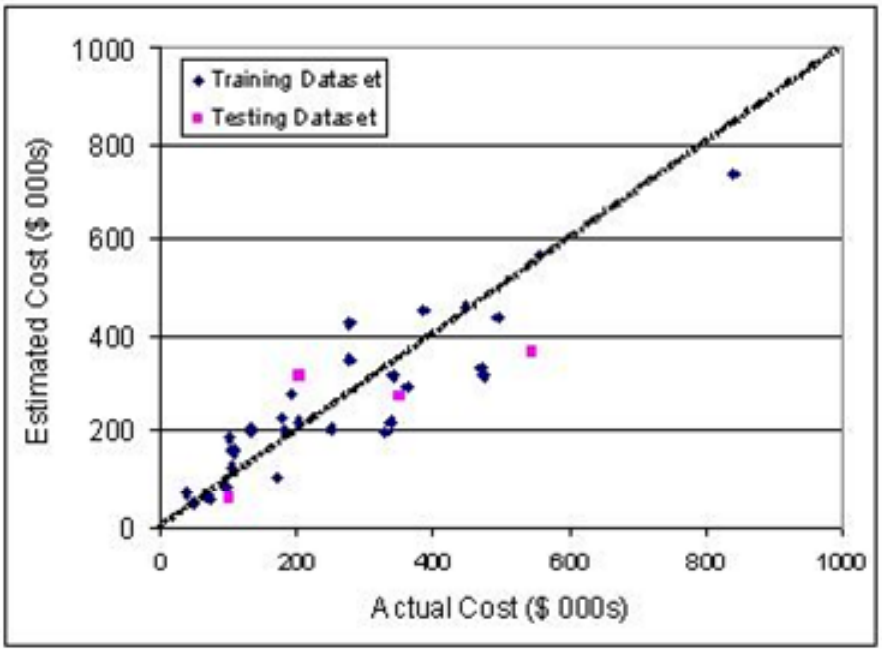


Figure 18: Results of Network Training and Testing (Nevada)

The effects of weather information on costs were analyzed and the analysis results of *WI_F* and *WI_A* are illustrated in Figure 19. It was found that the mean cost decreased with increased frequency or accuracy. The overall slope of the accuracy curve is steeper than that of the frequency curve, indicating that winter maintenance costs are more sensitive to the accuracy of weather information.

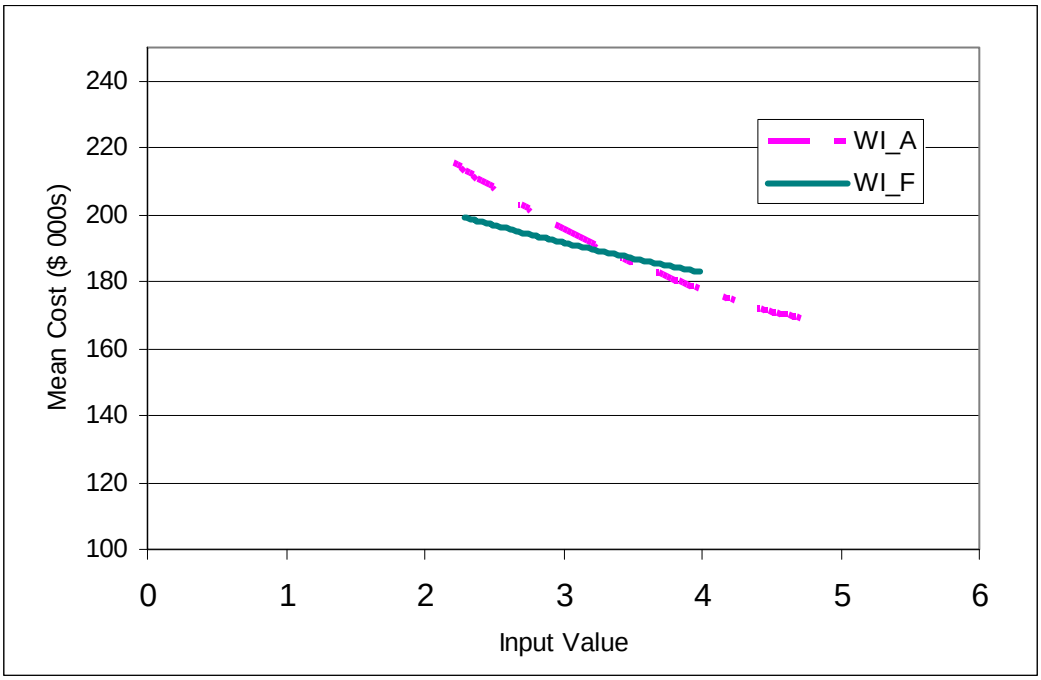


Figure 19: Impacts of Weather Information on Costs (Nevada)

Finally, a benefit–cost analysis was conducted for this case. The three scenarios defined in the previous case study were used for comparison. The results of the benefit–cost analysis are presented in Table 25. The benefits were calculated for the winter season of 2006–07. The weather information costs (on a yearly basis) include the following two aspects:

- RWIS maintenance cost: $81,901/year.
- Private-sector weather forecast services: $98,682/year.

Table 25 shows that the benefits of using weather information are greater than weather information costs, with a benefit–cost ratio of 3.2. It was also found that given existing weather information accuracy, increasing the frequency of using weather information can bring more benefits to winter maintenance. The benefits of Alternative 2 over Alternative 1 are about $197,000, or in other words the benefits can be furthered increased by thirty-four percent.

Table 25: Benefit–Cost Analysis (Nevada)

Scenarios	Cost ($ 000s)	Benefits ($ 000s)	Weather Information Costs ($ 000s)	Benefit-cost Ratio
Base	9,501	N/A	N/A	N/A
Alternative 1	8,924	576	181	3.2
Alternative 2	8,728	773	N/A	N/A

The benefit–cost analysis tends to be conservative because the benefits were calculated for only the 34 maintenance units (crews) in the dataset. The total winter maintenance costs in Nevada were about $12.8M during the winter season of 2006–07. More benefits are expected when applying this evaluation method to all maintenance units in the state.

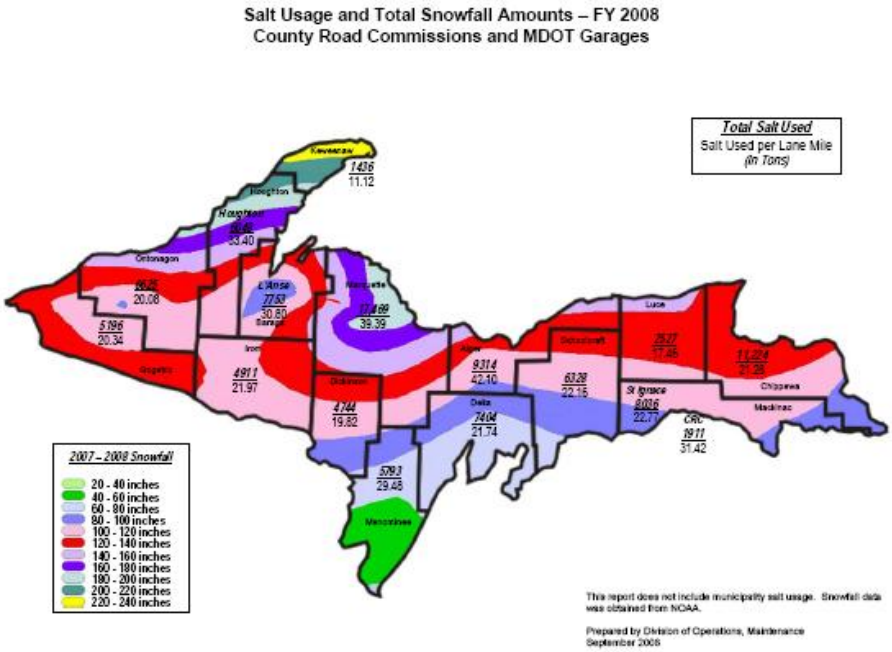
6.5 Michigan Case Study

6.5.1 Study Data

Data collection for the Michigan case included two components: winter maintenance data for the winter season of 2007–08, and weather use information during the corresponding winter season. The basic maintenance unit for this case study is county-based. The state includes 83 counties.

Winter maintenance cost information was obtained from Michigan DOT, which included winter operations cost, winter road patrol cost, and other winter maintenance cost for each county. Only winter operations costs were used for the benefit–cost analysis; it contributed to approximate 90 percent of total costs. The (centerline) lane miles maintained in each county during this winter season were calculated using maintenance cost and cost per (centerline) lane mile.

To obtain winter severity index values for counties, the research team first tried to download weather data from the NCDC database. However, only limited number of weather stations had downloadable data needed for this study. Missing data was also an issue with the downloaded data. Thus, the team decided not to use NCDC data for calculating winter severity index values. Instead, snowfall information during the past winter season was used to develop winter severities. In Figure 20, total snowfall amounts in each county are portrayed using different colors, each of which represents a certain interval of snow amount (i.e., 20–40 inches is represented by light green, 40–60 inches is dark green). The maximum snowfall in the northernmost area was between 220 and 240 inches during the 2007–08 winter season.



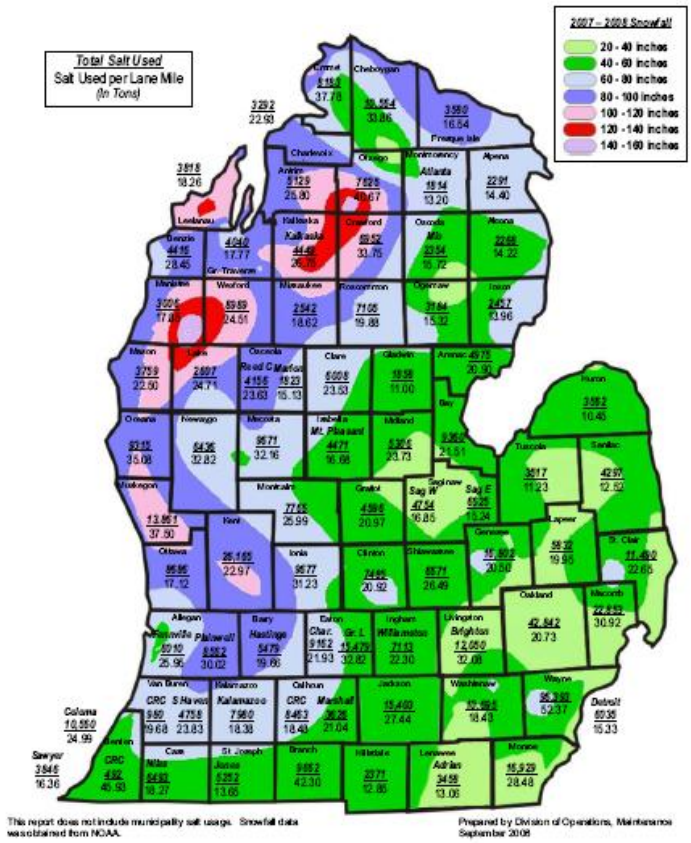


Figure 20: Snowfall in Michigan (2007–08)

In order to calculate snow amount, each county was broken into one or more sections of uniform snow accumulation, represented by a single color from the map in Figure 20. Since each color represented an interval of snow amount, the mean value of this interval was used. For example, red areas, which represent values from 120 to 140 inches, were considered 130 inches. Moreover, the sizes of different sections that formed a county were calculated in ArcGIS (http://www.esri.com/software/arcgis/). Using these values, the snowfall of each county was computed using the weighted-average method ("area" as the weight).

An online survey was distributed by Michigan DOT (MDOT) to learn about weather information use in the state. A total of 57 responses were received. The respondents included representatives of county road commissions, MDOT direct maintenance coordinators/supervisors, MDOT direct transportation maintenance workers, and others (e.g., MDOT engineers). The survey results are presented in the report of Technical Memorandum 3 of this project (72).

It was found that Michigan winter maintenance personnel had low frequencies of using weather information (observations and forecasts). This might be partly due to the lack of weather resources in the state. Eighty percent of respondents said that there were no RWIS sites located within their geographic areas of responsibility; six of the nine respondents using RWIS information indicated that they used weather information less than daily. Moreover, approximately half of the respondents said they did not use weather forecasts provided by private-sector providers for winter maintenance. Some respondents expressed that they stopped using private-sector weather forecasts because of costs. Several respondents replied that they did not use either RWIS observations or weather forecasts for winter maintenance.

The calculation of the frequency of weather information use in each county was based on observations and forecasts. A significant part of the frequency values were between 1 (never use) and 2 (less than daily). This is different from the previous two case studies, in which the frequencies of using weather information (observations and forecasts) were higher than 2. The Michigan DOT indicated that many winter maintenance units cancelled their weather forecasting service in the last few years and utilized free online weather forecasting. Thus, two assumptions were made in calculating the accuracy and frequency of weather information use for each county.

- If the county did not use weather observations (or forecasts), the default value of frequency use of observations (or forecasts) is 2 (less than daily, and only when storms are forecast or occurring).
- If a survey did not indicate the accuracy of weather observations or forecasts, the default accuracy of weather information (observations or forecasts) is 3 (the accuracy level of free weather service).

Based on available information, five variables of lane miles (*LM*), snowfall (*SF*), frequency of using weather information (*WI_F*), accuracy of weather information (*WI_A*), and level of anti-icing (*AI*) were used for developing the winter maintenance cost model. The statistics of these variables are summarized in Table 26. After preprocessing input data, 22 samples were qualified for benefit–cost analysis. The sample size is relatively small mainly due to replicated responses for the same county in the survey; also, some respondents did not represent any specific county.

Table 26: Statistical Descriptions of Variables (Michigan)

Variables	Mean	Standard Deviation	Coefficient of Variation (%)
LM (mile)	463	549	119
SF (inch)	57.6	21.4	37
WI_F	2.38	0.46	19
WI_A	3.36	0.57	17
AI	2.97	1.42	48
WMC ($)	1,745,459	2,274,041	130

The average frequency of weather information use among the 22 samples was 2.38. If the use of free weather services is not taken into account, the average value (of using RWIS and for-fee weather service) for the 22 samples becomes 1.77, which is between no use of weather information and less than daily usage.

6.5.2 Sensitivity Analysis

The 22 samples were normalized for sensitivity analysis. The normalized dataset was further used for network training, and the trained network consisted of an input layer with five input variables, a hidden layer with four nodes, and an output layer with one output variable. Six runs were conducted to examine the MSEs of training. As shown in Figure 21, 50 epochs are enough for the training of this dataset to avoid overtraining.

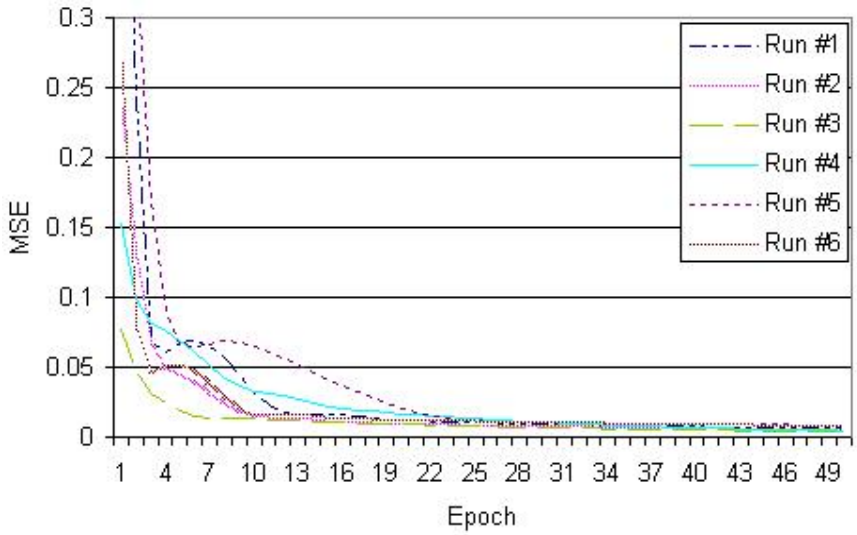


Figure 21: Learning Curves (Michigan)

Sensitivity analysis was conducted for each of the six runs (trainings). The analysis results are shown in Figure 22, in which the sensitivity values are the means of the six trainings. Winter maintenance costs (*WMC*) were highly sensitive to variations of *LM*. However, the sensitivity value of *SF* is the lowest, which indicates that using snowfall information might not reflect the actual winter severities within this state.[6] The values of *WI_F*, *WI_A*, and *AI* are 0.05, 0.10, and 0.14, respectively. Based on the analysis results, all of these five variables are included in the further modeling of winter maintenance costs.

[6] This seems reasonable since experience has shown that treating for a 2-inch snow storm can be more costly than treating one 8-inch snow storm. Also, treating a freezing rain event might very well be more expensive than treating an 8-inch snow storm.

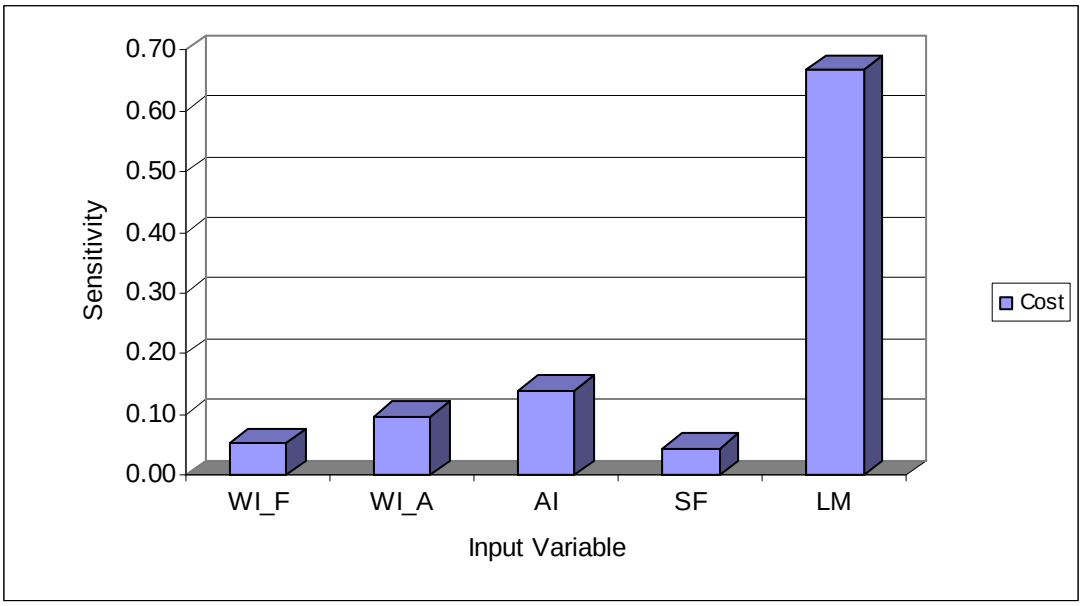


Figure 22: Sensitivity Analysis for Input Variables (Michigan)

6.5.3 Impacts of Weather Information Use on Costs

The original dataset with 23 samples was divided into a training dataset (19 samples) and a testing dataset (3 samples). The same network configuration in the sensitivity analysis was used for trainings with 50 epochs. Training results are shown in Figure 23. The R^2 (regression coefficient) value of the training dataset was 0.91. The results show a strong relationship between the actual and estimated costs, although the sample size is relatively small.

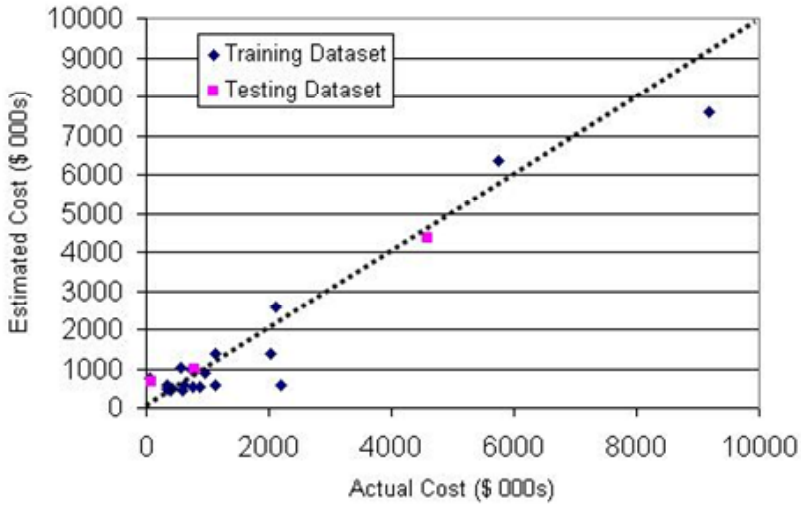


Figure 23: Results of Network Training and Testing (Michigan)

The effects of weather information use on costs were analyzed and the analysis results of *WI_F* and *WI_A* are shown in Figure 24. Similar to the previous two case studies, it was found that the mean cost decreased with increased frequency or accuracy. The overall slope of the accuracy curve is steeper than that of the frequency curve, indicating that winter maintenance costs are more sensitive to the accuracy of weather information.

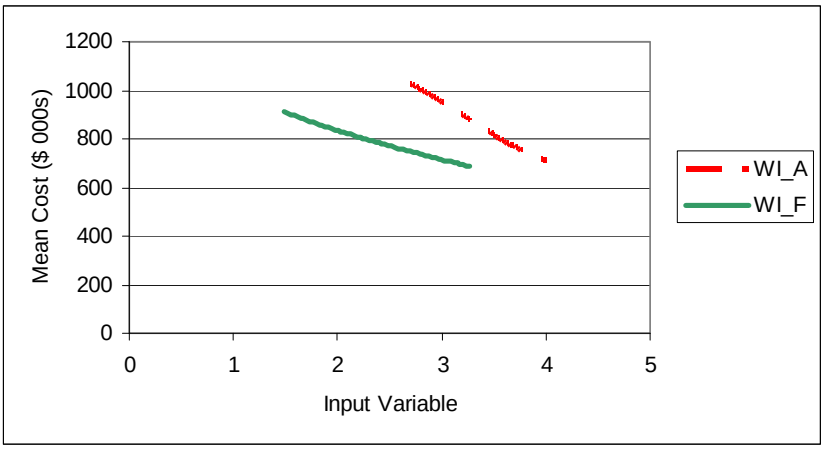


Figure 24: Impacts of Weather Information on Costs (Michigan)

Finally, a benefit–cost analysis was conducted for this case. The results of the benefit–cost analysis are presented in Table 27. The benefits were calculated for the winter season of 2007–08. The weather information costs (on a yearly basis) only include weather forecast service costs:

- Private-sector weather forecast services: $7,140/year. Michigan DOT purchased weather forecasts for five counties at $1,428/year each. It should be noted that nine counties were identified as using weather forecasts during this winter season.
- Michigan DOT did not pay for RWIS maintenance costs during this winter season. Of the 22 counties, five counties were identified as using RWIS information.

The total maintenance costs for the 22 counties during the winter season were about $31.53 million.[7] The benefits of using weather information are $0.27 million dollars, which is approximately equal to 0.9 percent of the total winter maintenance costs. However, the benefit–cost ratio is very high due to the low costs of obtaining weather information. The analysis also shows that increased use of weather information could save more on winter maintenance costs.

[7] The statewide winter maintenance operations costs were around $68.4 million during the 2007–08 winter season, based on cost information from 67 counties.

Table 27: Benefit–Cost Analysis (Michigan)

Scenarios	Cost ($ 000s)	Benefits ($ 000s)	Weather Information Costs ($ 000s)	Benefit-cost Ratio
Base Case	31,801	N/A	N/A	N/A
Alternative 1	31,530	272	7.4	36.7
Alternative 2	30,598	1,205	N/A	N/A

6.6 Summary

In this chapter, the research team proposed a winter maintenance cost model and a methodology for analyzing the benefits of using weather information. To develop the cost model, related data were collected from state DOTs and through online surveys (or phone interviews) of winter maintenance personnel. The methodology was applied to three case studies for the states of Iowa, Nevada, and Michigan. The findings from the case studies were summarized as follows:

- The use of weather information varied among the three case study states. The average frequency values of using RWIS and private weather forecasts were 2.75 (Iowa), 3.49 (Nevada), and 1.77 (Michigan), respectively. Maintenance personnel in Michigan used more free weather services than the other two states. The differences between states might have been due to their levels of trust in weather information services (e.g., accuracy) and associated service costs.
- Compared with frequencies, the average accuracies of weather information among the states had smaller variations, ranging from 3.4 to 3.6. (Accuracy takes the values of 1 to 5. A value of 3 means that the accuracy of fee-based weather services is the same as free weather services; the higher the value, the better.) The survey results indicated that fee-based weather information was more accurate than free weather services, especially for the Iowa and Nevada cases.
- The case studies found that weather information use had positive effects on winter maintenance costs. Case studies collectively showed that winter maintenance costs decreased with the increase use of weather information or its accuracy.
- It was found that accuracy had a greater effect on maintenance costs than frequency. In other words, winter maintenance costs were more sensitive to accuracy than frequency. Hence, the improvement of weather information accuracy is critical to achieving more savings in winter maintenance. Increasing the accuracy of weather information is anticipated to attract more customers to use that information.
- The benefit–cost analyses showed that the use of weather information could bring more benefits than costs. The benefit–cost ratios for the case studies are 1.8 (Iowa), 3.2 (Nevada), and 36.7 (Michigan). The Michigan case had the highest benefit–cost ratio due to low costs in weather service. However, further investigation of total winter maintenance costs and total savings found that the savings percentage was 5.6 percent (Iowa), 6.5 percent (Nevada), and 0.9 percent (Michigan), as shown in the following table.

Although the Michigan case had the highest benefit–cost ratio, the amount of benefits over total winter maintenance cost is the lowest. For this reason, benefit–cost numbers in this research study cannot tell the whole story. Actually, the benefit–cost ratios of the Iowa and Nevada cases are more representative numbers because the costs associated with weather information in these two states were based on statewide numbers, while the Michigan case was not.

Table 28: Maintenance Costs and Benefits

Case Study State	Winter Maintenance Costs ($ 000s)	Benefits ($ 000s)	Percentage (%)
Iowa	14,634	814	5.6
Nevada	8,924	576	6.5
Michigan	31,530	272	0.9

CHAPTER 7. SECONDARY RWIS BENEFITS

The benefit–cost analysis described in the previous chapter focused on comparing two weather information alternatives against a base case (assumed to be exclusive reliance on "free" information sources) to support winter maintenance activities. This analysis focused exclusively on how the quality and usage frequency of different sources of weather information could result in cost savings for winter maintenance operations. As was demonstrated, these economic savings outweigh the costs of improved information by a significant proportion. This analysis is valuable in justifying investment in and expansion of RWIS ESS networks. However, this chapter focused primarily on winter maintenance applications. There may a number of other applications that could be spun off of existing or enhanced RWIS. A transportation agency may find additional ways to use these same sources of weather information to yield even greater benefits with minimal or no additional cost.

While there is some uncertainty regarding the costs of upgrading the RWIS infrastructure to support the secondary RWIS applications, there is even greater uncertainty regarding the range of potential benefits. For example, the safety benefits of a dynamic warning system will depend on existing crash rate, the percentage of crashes that may be realistically averted through the dynamic system, traffic volume, and other factors. In some cases, such as improved traveler information, the benefits will not be monetizable at all. Recognizing this, the research team identified the types of benefits that would be realized for each secondary RWIS application.

The purpose of this chapter is thus to identify the potential benefits and costs that would be associated with using RWIS beyond the winter-maintenance-related benefits. This chapter will consider a range of potential secondary applications of RWIS, the cost of adaptations and expansions required to provide those applications, and the potential benefits that may be realized. These will be described and summarized in the following sections.

7.1 Potential RWIS Extensions

Weather information from RWIS is mainly used by maintenance personnel, but it can be also useful to other users such as traffic managers to improve mobility and safety of traffic, travelers to obtain real-time weather information and plan their trips, and motorists to know about potential danger on the road. Hence, this section seeks to identify potential extensions of RWIS and their associated benefits and costs. The benefits and costs will be also described but are not monetized in the study because they are subjective and difficult to quantify (6).

7.1.1 Enhanced Traffic Signal Timing

Studies have proved that adverse weather can reduce traffic speed both on freeways and arterial streets and increase traffic delay. As degraded visibility or pavement friction may reduce traffic speed on arterials, signal timing plans developed under dry and clear conditions may not be optimal in inclement weather. For instance, a study in the city of Anchorage, Alaska, found that signal timing parameters used in the summer were not appropriate for the winter and extreme conditions (73). The impacts of weather on arterial traffic flow were summarized in several

studies (e.g., 74, 75). Increased demands on the transportation system mean that optimization of signal timing under poor weather has become a very important part of traffic signal operations.

Numerous simulation studies have demonstrated how altering green time and cycle lengths during adverse weather conditions can improve intersection level of service. The Anchorage study showed that the timing plan for inclement weather decreased travel time by 13 percent and average delay by 23 percent (73). In the simulation, traffic flow parameters of saturation flow, vehicle speeds, lost time, and capacity were modified based on real-world measurements. A study by the Minnesota DOT (MnDOT) collected weather data from RWIS and used them to do signal timing optimization under inclement conditions for a street network in Minneapolis (76). The simulation modified saturation flow rates, average speeds, and lost time for inclement conditions and the results showed a 13 percent reduction in average vehicle delay and a 6 percent reduction in the average number of stops per vehicle. This study also observed that traffic volumes during inclement weather were 15 to 20 percent lower than those collected during the same time period (3–8 p.m.) on a normal day. This suggests that changing cycle lengths could also help improve signal operations during inclement weather (75).

While developing inclement weather timing plans can improve level of service, the plans should be activated based on some "warrants." As recommended by Perrin et al. (75), four general factors including the severity of weather conditions, duration of storm events, area of influence, and traffic flows should be considered before applying new timing plans.

The operation of weather-responsive traffic signal timing control might follow an architecture similar to the one shown in Figure 25. In the field, RWIS ESS may connect with the signal controller and provide road weather information to a traffic management center; and traffic detectors can provide real-time traffic data (e.g., traffic volume). Based on the input information, the traffic signal control system at the TMC may automatically execute new timing plans under inclement weather conditions. The change of signal timing plans may be also done manually by traffic managers based on their judgments.

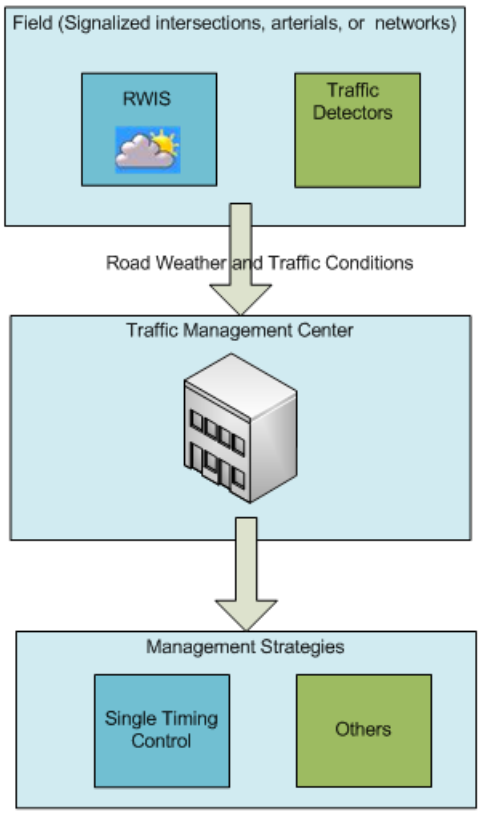


Figure 25: Weather-responsive Traffic Signal Control

To develop inclement timing plans, weather information collected from RWIS can be the best source because they are designed for the road environment. The costs of such applications may include the communications-related costs (i.e., computer hardware and software, maintenance of equipment) between RWIS (and/or other weather sources) and Traffic

Management Center (TMC) and the cost of developing new timing plans. Once inclement timing plans are developed, they may be used for a relatively long period unless traffic demand, geometric design or other factors have significantly changed. Thus, the amortized costs to enhance traffic signal operations tend to be low, but the potential benefits of adopting new timing plans may be considerable as shown by the studies mentioned above. The potential benefits can mostly be reflected by reduced vehicle delay and less fuel consumption (as a result of reduced travel time and fewer stops).

7.1.2 Weather-Responsive Operations

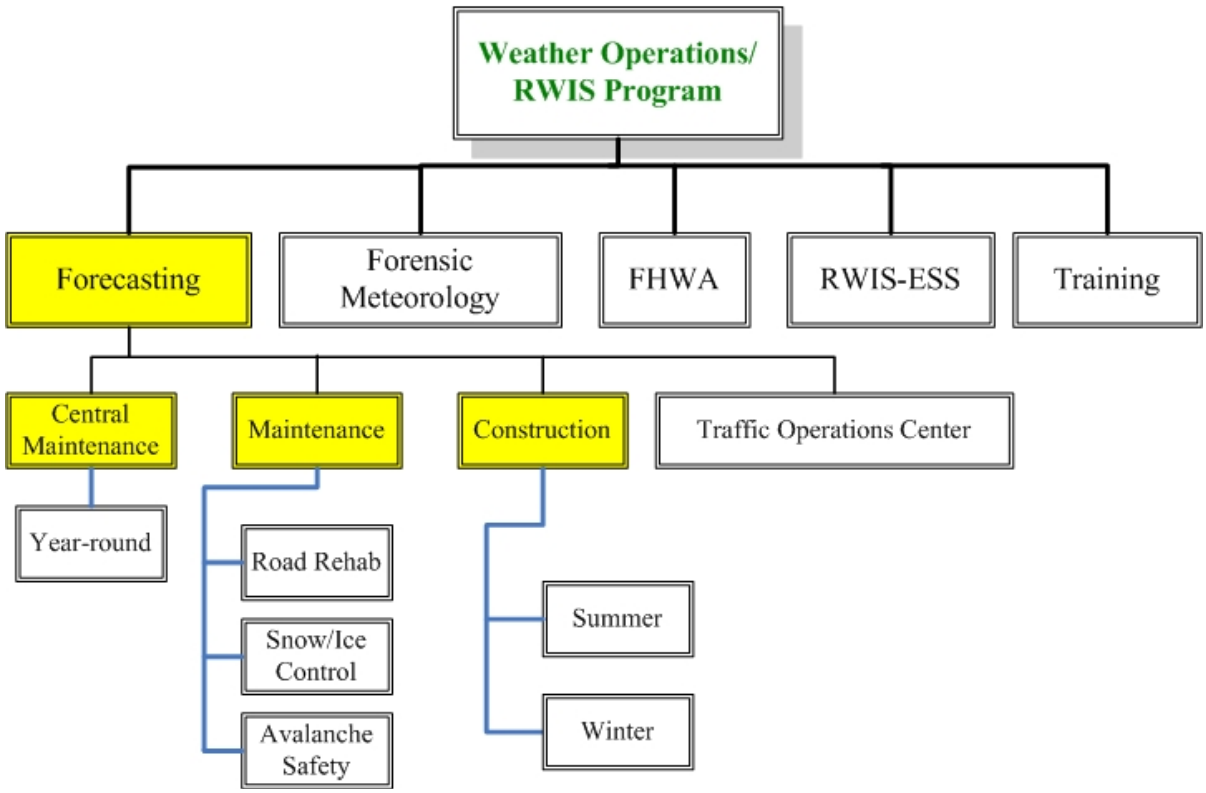
Studies have been conducted to explore the costs of traffic congestion as well as weather-related costs. It was estimated that a user cost of $78 billion per year is associated with traffic congestion (77), with the vast majority of these costs being borne in urban areas. Another study estimated that around 15 percent of congestion is due to weather events (78). These findings imply that there could be potential benefits in integrating weather information into transportation operations, which is so-called *weather integration.*

A recent FHWA study (79) defined weather integration as an activity that "supports a TMC's ability to manage traffic, dispatch maintenance forces, and address weather-related emergencies. This is accomplished by providing TMC operators with accurate and timely weather and road condition information, effectively integrating weather and traffic information, and providing automated notifications and decision support." The study stated that integration of weather elements is "a catalyst and tool for enhancing operational performance" (79).

The overall extent of weather integration, as identified by the FHWA study, can be characterized by five dimensions: operational integration, physical integration, technical integration, procedural integration, and institutional integration. Operational integration represents the ways in which data and information are shared and used by TMCs and connected agencies, organizations, and systems. To have successful operational integration, this dimension needs to be supported by the other four dimensions. The study presented three operations strategies including mitigation, sourcing, and analysis. The mitigation strategy was first provided by a weather-responsive traffic management study (80). This strategy includes advisory, treatment, and control strategies, of which the advisory strategy is the most widely practiced and integrated.

A success story of weather integration is the Utah DOT's Weather Operations/RWIS Program (81). Currently, this program assists the DOT operations, maintenance, and construction functions by providing detailed, often customized, area-specific weather forecasts. Established under the UDOT Traffic Management Divison, the program has two main components. First, the Weather Operations component features four staff meteorologists stationed in UDOT's TOC, providing year-round weather support for winter maintenance, road construction and rehabilitation projects, TOC operations, avalanche safety, planning, risk management, training, and incident management. With the staffed meteorologists, quality control of weather forecasts is ensured. Weather briefings are conducted in the TOC on a daily basis, involving TOC personnel, area supervisors, and maintenance foremen. In addition, the program provides tailored crew-specific forecasts in a text format for all 82 UDOT maintenance sheds. Another component of the program is the ITS component, which manages 48 RWIS stations and expert systems such as bridge spray systems, high wind alerts, and fog warnings (28).

As shown in Figure 26, the program provides various services to numerous customers within UDOT. It provides the Office of Central Maintenance with year-round, long-term weather forecasts that are mainly used for planning in terms of materials (storage and purchasing), staffing, and equipment. It provides construction engineers and contractors with weather forecasts for new construction and renovation projects, which are mainly used to plan for staffing, materials, and equipment.



(Source: 81)

Figure 26: Chart of UDOT Weather Operations/RWIS Program's Services

The extent of weather integration in a TMC depends on the institutional landscape, weather exposure, transportation infrastructure, and weather information needs in the state or region (79). For this reason, the potential benefits of weather integration vary depending on the conditions and level of integration at a TMC. However, several potential benefits of weather integration may be realized. These benefits that have been experienced by TMCs may include (79):

- Direct benefits depending upon the quality and availability of advisory strategies, available transportation systems control actions, and dispatch needs of integrated agencies;
- Improved access to all regional information;
- Ability to coordinate and pool resources to accomplish operations not currently possible;
- Improved clarity of roles and ability to communicate both in current operations and in future investments;

- Improved cost-effectiveness through reduction in the need to deploy duplicate resources;
- More efficient evacuation activities through integration of traffic operations tools, strategies, and procedures;
- Improved public safety through reduced incidents;
- A common focal point for TMC-related agencies enhancing institutional, procedural, and operational integration;
- More timely and accurate information provided to the traveling public, thereby increasing customer safety and satisfaction; and
- Better prepared TMC operators to address adverse weather on the transportation system in terms of appropriate staffing and implementation of traffic advisories and control strategies.

The costs of weather integration are somewhat difficult to define because they spread over several divisions within a DOT (81). The FHWA study (79) noted that the accounting of costs was cited as a challenge by many TMCs, which found it difficult to show justification for the allocation of funds. Weather-integration-related costs may include the procurement of sensing equipment and computer hardware and software, maintenance of installed equipment, staff to coordinate the weather information integration activities, or contract services to provide weather forecasts (79).

7.1.3 Dynamic Warning Systems

A more direct way to integrate weather into transportation operations is to communicate information directly to the traveler through autonomous dynamic warning systems. Readings from one or more RWIS-ESS may be used to activate systems to warn motorists of real-time hazards. For example, dynamic message signs on Interstate 90 over Snoqualmie Pass in Washington State display temperature readings, helping motorists to understand the relative risk of icy pavement. Automated systems have been successfully deployed that address challenges related to icy pavement (Wyoming), high winds (Nevada), and reduced visibility (Tennessee, Utah, California and others). The location of RWIS ESS will often be coincident with the location of weather-related safety hot spots, providing a convenient opportunity to add a warning system.

Examples of automated road weather warning systems are provided in Table 29, which presents the location, targeted environment, data collection equipments, system inputs, and the objectives of systems. The targeted environment includes (but is not limited to) three categories: snow and ice, low visibility, and high winds. Some of the systems were designed to address a couple of weather events (i.e., low visibility and high winds).

Table 29: Examples of Road Weather Warning Systems

Warning Systems	Location	Targeted Conditions	Data Collection Equipments	System Inputs	System Outputs	Objective
Washington State Snoqualmie Pass variable speed limit system	I-90 Snoqualmie Pass	Snow and ice (considerable winter snow accumulation)	Radar speed detectors, and RWIS	Speed and road weather information	Advisory messages and speed limits on DMS	Reduce crashes caused by driving too fast for conditions and speed variations
Wyoming dynamic speed warning system	Between Burgess Junction and Lovell on US 14	Snow and ice (high snowfall accumulations and blowing snow)	Radar speed detectors, classification sensors, and RWIS	Vehicle speed, classification, and road weather elements	Warning on DMS directly at the driver of a specific vehicle	Provide warnings to mostly RV traffic
Wyoming ice detection and warning system	A bridge deck in a remote canyon on U.S. 131	Snow and ice (high snowfall accumulations and blowing snow)	RWIS	Road weather elements (moisture, air temp, pavement temp, etc)	Activation of flashing lights (attached to a static “ice on bridge” sign)	Provide increased safety for the traveling public
Idaho storm warning system	I-84, milepost 224 to milepost 269	Low Visibility/Snow and ice (blowing snow or dust)	RWIS	Road weather elements (visibility, air temp, wind, precipitation, pavement conditions)	Warning messages (i.e., low visibility) on DMS (turned on by traffic managers)	Reduce multivehicle crashes related to reduced visibility
New Jersey Turnpike variable speed limit system	New Jersey Turnpike	Low visibility (fog, snow, and ice)	Inductive loops and RWIS	Speed, volume, and road weather elements (wind, precipitation, etc.)	Speed limit as well as regulatory and warning message on DMS and HAR	Provide early warning to motorists of slow traffic or hazardous road conditions

Warning Systems	Location	Targeted Conditions	Data Collection Equipments	System Inputs	System Outputs	Objective
Nevada variable speed limit system	I-80	Low visibility (fog)	Speed loops, visibility detectors, and RWIS	85th percentile speed, visibility, and pavement conditions	Regulatory speed limit via VSL (Variable Speed Limit) signs	Improve safety under foggy conditions
Tennessee fog detection warning system	I-75 near Tiftonia	Low visibility (fog)	Fog detectors and radar speed detectors	Visibility and speed	Reduced speed message on DMS	Reduce crashes due to heavy fog
California motorist warning system	Stockton-Manteca area of San Joaquin County	Low visibility/High winds (wind-blown dust in summer and heavy fog in winter)	Dual loops, and RWIS	Speed, volume, and road weather elements (precipitation, relative humidity, wind, etc.)	Warning message on DMS; using flashing amber lights atop patrol vehicles	Improve traffic safety during low visibility and high wind conditions
Montana high wind warning system	I-90 in the Bozeman/ Livingston area	High winds	RWIS	Wind direction and speed	Warning, restriction, or typical restriction message on DMS	Improve safety under high wind conditions
Nevada high wind warning system	Washoe Valley on US 395	High winds (very high crosswinds)	RWIS	Road weather elements (wind, surface condition and temp, air temp, etc.)	Advisory or regulatory message on DMS; broadcasting message via HAR	Warning of high wind conditions and prohibits travel of designated vehicles during severe crosswinds

(Sources: 82, 83)

The costs of warning systems will vary based on system design, but the majority of them are hardware-related costs such as ESS, dynamic message signs, communication systems and/or vehicle detectors and maintenance. Thus, the total budget for the implementation of road weather warning systems will not be low unless it is developed based on existing RWIS-ESS. However, as these systems are installed for hot spots, the benefits of deploying such systems could be substantial. Motorists will benefit from them directly with safer and more comfortable driving. Although there are few evaluations of the effectiveness of these systems, data have shown that lives have been saved by using road weather management systems. For instance, before the implementation of the Tennessee fog detection warning system, there was a 99-vehicle crash in December of 1990 with 12 fatalities and 42 injuries; there have been no fog-related crashes since the system was activated in 1993 (82).

7.1.4 Anti-icing Spraying System

Anti-icing is the application of chemical freezing-point depressants to the roadway in advance of deteriorating weather conditions, in order to prevent black ice formation and to prevent or weaken the bond between ice and the road surface. Fixed Automated Spray Technology (FAST) is an important tool for anti-icing and enables winter maintenance personnel to treat potential conditions before snow and ice problems arise (84).

A complete FAST system includes a spray subsystem (that delivers the anti-icing chemical onto the road surface) and a control subsystem (that triggers the spraying action). The control subsystem consists of RWIS, RPU, data server, software application, and electronic control and triggering devices. RWIS sensors are used for early frost and ice warning (84). Like dynamic warning systems, FAST systems are installed at key locations such as bridges. Thus, the benefits of deploying such systems could be substantial with safer driving during inclement weather.

A survey was conducted and found that the cost of FAST installation varied greatly depending on site location, accessibility of existing utilities, the level of system sophistication, and market factors; an automated RWIS station associated with each FAST installation was around $93,000 (84).

Several studies have been conducted to evaluate FAST systems. In 1993, a German study found a benefit–cost ratio of 1.9, in which benefits include saved costs of road safety and traffic conditions (85). A Washington study considered safety benefits and reported a benefit–cost ratio of 2.36 (86). New York City DOT verified that the FAST system can "*significantly and cost effectively enhance motorist's' safety during snow and icing conditions relative to the present over-the-road (trucks) methods of application*" (87).

7.1.5 Traveler Information

Another way that weather information can provide value is by providing it directly to the traveler. Surveys of traveler information services have routinely noted that weather information, whether provided through text or camera images, is the most frequently requested type of information (88).

A 2004 national survey showed that states have used several methods to provide road weather information to the traveling public, as shown in Table 30 (89). The most commonly used methods reported by the 48 states responding to the survey were Internet web sites, 511 telephone system, and roadside warning devices. Over 70 percent of those states used Internet web sites to disseminate road weather information to travelers. A sophisticated example of these web sites is the Iowa DOT's WeatherView (http://www.dotweatherview.com/), which reports road and airport weather conditions to the public based on statewide deployed RWIS and Automated Weather Observing System (AWOS). Other web sites, such as Oregon Department of Transportation's TripCheck (http://www.tripcheck.com), which provide weather information from RWIS as a supplement to other types of traveler information, are more typical. While it was reported that one state (Minnesota) used in-vehicle devices, it was found that this state actually did not select this method in the survey (89).

Table 30: Methods for Providing Road Weather Information to the Traveling Public

Number of States Surveyed / Returned Surveys	50 / 48	
Number of States Using the Following Methods to Provide Road Weather Information to the Traveling Public	Roadside Warning Devices (e.g., DMS, HAR)	19
	In-vehicle Devices	1
	Interactive Kiosks	5
	Personal Communication Devices (e.g., PDAs, pagers)	2
	Dedicated Television Channel	3
	Fax	3
	E-mail	4
	Internet Web Site	34
	511 Telephone System	22
	Telephone Number other than 511	12

(Source: 89)

One barrier to providing weather information service to travelers is that these road weather information systems typically provide information tailored to specific jurisdictional lines, whereas rural trips may span multiple jurisdictions. In addition, while many rural agencies and districts have sought to provide traveler information, there is considerable variation in the level of information provided and how to access it. This makes it difficult for a traveler to gain "one-stop" access for weather information for the length of a longer trip, especially in and through rural areas.

By accessing Internet web sites, calling 511, or using other methods, users are able to know about general weather conditions and prevailing conditions on a route, check weather for special events, and make decisions for travel time and travel route. This use of pre-trip traveler information by travelers can be useful in improving traveler safety, reducing vehicle delay and enhancing traveler security and convenience, especially under inclement weather.

The costs of providing road weather information to the traveling public, given an existing RWIS infrastructure, depend on the sophistication of the interface but are relatively low. Depending on which methods are used, the costs mainly include the establishment and maintenance of platforms (i.e., web site, telephone system) for travelers to access to road weather information. Some methods such as e-mail may require less cost.

7.1.6 ITS Nodes

RWIS hardware mainly consists of three systems: the environmental sensors, the remote processing unit, and communications capabilities (32). The whole system requires consistent power to be functional. Therefore, installation of an RWIS brings with it a power and communications backbone. This backbone can support a variety of other field technologies. Sharing the power and communications backbone, especially in a rural environment, can reduce the cost of adding a new technology.

One technology that effectively complements RWIS, especially for winter travel, is Closed Circuit Television (CCTV) cameras. CCTV cameras may be used for remote visual verification of actual weather conditions (e.g., visibility, pavement conditions). This can be useful for winter maintenance operations, and is also highly valued for traveler information (see Section 7.1.4). In the case that RWIS is installed in the vicinity of a crash-prone location, the RWIS hardware could also be beneficial for the deployment of dynamic warning systems, which may consist of vehicle detectors and message signs in addition to RWIS, to reduce vehicle crashes under adverse weather conditions.

Since the cost of communications can be a deciding factor when installing and implementing RWIS (32), the savings from sharing communications as well as power with additional technologies will be considerable. The savings will be even more if a server is installed for the communications system of RWIS in that several stations can be tied into one micro-server and can relay information by a local call versus a long distance call. The additional technologies can also benefit from using the server. It is important to note that the design and implementation of communications systems of new technologies should be compatible with existing systems.

7.1.7 Use by Other Agencies or Entities

The RWIS network can be beneficial for sharing road weather information with other interested agencies/entities. The FHWA survey mentioned earlier found that many transportation agencies share road weather information with other agencies; the number of states doing so is shown in Table 31 (89). In addition to other maintenance crews, road weather information can also be shared with emergency management agencies, commercial vehicle operators, school districts, and others not listed (e.g., USPS, statewide media, military). Half of the states have shared road weather information with public safety agencies such as highway patrol. Around one-third of

them shared such data with traffic management centers (addressed under weather integration; see Section 7.1.2) and emergency management agencies.

RWIS data can also be shared beneficially across state lines to assist in forecasting and tactical planning of winter maintenance operations. A typical example of this is the *Clarus* initiative. Several multi-state groups have connected their RWIS ESS networks to provide data to the *Clarus* system for ready access by a variety of agencies. As of December 31, 2008, there were approximate thirty states in the United States and three Canadian provinces that had established connections to feed their DOT ESS data into *Clarus*; many other states were under construction or considering connection (90).

RWIS ESS can also be used to expand the surface weather observation network. For example, as mentioned above, the Iowa DOT's WeatherView incorporates weather observations from RWIS and AWOS to expand the surface network. This will make its service useful for more users who may be interested in weather conditions along a specific route, around an airport, or both. In addition, the combination and fusion of surface weather data from different sources can be valuable in initializing and calibrating weather and road weather forecast models. National Weather Service (NWS), military, and private weather service providers use surface weather data to develop weather products, short-range forecasts, and forecast verification, and as input to locally run weather forecast models (30).

Table 31: Sharing Road Weather Information with Other Agencies/Entities

Number of States Surveyed / Returned Surveys	50 / 48	
Number of States Sharing Road Weather Information with the Following Agencies/Entities	Emergency Management	17
	Public Safety (e.g., law enforcement, highway patrol)	21
	Transit Operators	6
	Information Service Providers	7
	Commercial Vehicle Operators	6
	School Districts	3
	Traffic Management Centers	14
	Maintenance Crews	21

(Source: 89)

It should be noted that not all RWIS sites will have equal value in calibrating or verifying weather models. A FHWA publication on guidelines for siting ESS noted that they may be located primarily for regional (network) or local perspectives. A regional site is designed to collect weather information along a given road segment, while a local site is designed to provide weather observations along a short segment of roadway or bridge for specific objectives (e.g., slippery pavement, high wind, low visibility) (30). Regional sites would likely provide better value to weather models.

7.1.8 Research Opportunities

RWIS provide real-time, highway-specific weather information that can help in a variety of research activities where the effects of weather are an important variable. Weather may be the primary variable of interest in a study (for example, quantifying the effects of weather on traffic flow parameters), or it may be a supporting variable (for example, comparing long-term behaviors of pavements).

Considerable efforts have been conducted to learn about the effects of weather on traffic operations (e.g., speed). Appendix E lists some past studies on the effects of weather on safety and speed. All these studies used road weather data collected from RWIS to explore traffic characteristics under various weather and pavement conditions. The results will help traffic analysts know about the influence of various weather conditions on traffic flow. Thus, they will be better prepared for traffic operations and incident management when they are provided specific road weather information, especially adverse weather information. For example, based on the findings of effects of weather on traffic speed, traffic analysts are able to develop (or use) speed adjustment factors and implement safer speeds for motorists. Another example is that the Highway Capacity Manual (HCM) incorporated research findings to quantity the reduction in traffic facility capacity under varying conditions (91), which makes it easier for traffic analysts to apply research results to practice. Travelers will benefit from the improvement of traffic management and operations with lower crash rates, reduced vehicle delay, and better trip planning. Findings in these studies will further assist researchers in related areas to grasp state-of-the-art knowledge and improve the accuracy, depth, and width of weather effects on traffic safety and operations.

Weather stations can also be used to provide important information that can be used to strengthen experimental design for a variety of transportation research projects. For this reason, weather data collection is an integral part of many road testing facilities, including near-network facilities such as the Minnesota Department of Transportation's Mn/Road near I-94 and the University of North Dakota's Surface Transportation Weather Research Center Field Site adjacent to I-29, and off-network facilities such as the Virginia SmartRoad and the Lewistown, Montana, test facility.

7.2 Summary

This chapter provided a high-level summary of several secondary applications of road weather information. Table 32 lists these applications and their associated extents of application, potential benefits, and costs. Although not quantified, the potential benefits of applying road weather information to other practices could be substantial. On the other hand, the costs of secondary

applications are generally low since the majority costs of procurement, installation, and maintenance of RWIS are paid by winter-maintenance-related agencies.

Table 32: Summary of Secondary RWIS Benefits

Applications	Extent of Application	Potential Benefits	Potential Costs
Enhanced traffic signal timing	Rarely used, but expected to increase	Reduced vehicle delay; Less fuel consumption.	Low
Weather-responsive operations	Widely used by TMCs	Improved accessibility of information; Ability to coordinate and pool resources; Improved cost effectiveness; Improved public safety; More efficient evaluation activities; More timely and accurate information provided to the traveling public; Better prepared TMC operators to address adverse weather; Etc.	Varying depending on the allocation of funds among different divisions
Dynamic warning systems	Widely used	Reduced vehicle crashes; Reduced crash severity; More comfortable driving.	Moderate–High
Anti-icing spraying system	Widely used	Reduced vehicle crashes; Reduced Crash severity.	Moderate–High
Traveler information	Widely disseminated	Safer and more comfortable driving; Better trip planning for travelers.	Low
ITS Nodes	CCTV cameras widely used; Implementation of other technologies expected to increase	Provide power and communications system to other technologies.	Low
Network expansion	Widely used in northern areas	Provide road weather information to interested agencies/entities; Share data with other states; Help calibrate weather models.	Low–Moderate
Research opportunities	Considerable research opportunities	Better and more comprehensive understanding of weather effects on traffic operations; Better prepared traffic management under adverse weather to improve mobility and safety of traffic.	Low

CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this project is to provide a current benefit–cost assessment for weather information in winter maintenance. In the previous chapters, the research team summarized weather information resources used by transportation agency personnel, investigated how weather information was used to support winter maintenance operations, analyzed the benefits and costs associated with the use of weather information, and identified the potential benefits and costs that were associated with using Road Weather Information Systems (RWIS) beyond the winter-maintenance-related benefits. This chapter summarizes the findings and conclusions of this research study. The research team also provides recommendations for using weather information in winter maintenance.

8.1 Findings and Conclusions

The findings and conclusions of this research project are summarized below.

1) The survey of winter maintenance personnel found that free weather information sources, private-sector weather providers, and RWIS were the most widely used weather information sources. The other two sources, the road weather observation mesonets and Decision Support Systems (DSS), had fewer users; they usually collect road and weather data from two or more other sources such as the National Weather Service (NWS) and RWIS, and fuse them to generate information of interest for winter maintenance. Private-sector weather providers, who act similarly to mesonets and DSS, collect weather data from NWS or other sources to provide specialized information of current weather conditions and/or forecasts. Thus, free weather information sources and RWIS are the two primary direct sources for collecting road weather information.

2) Cost considerations and easy access contribute to the wide use of free weather information sources. However, these sources may have problems with timeliness and a lack of detail, which may result in the use of inaccurate weather information. Based on the survey of winter maintenance professionals, the accuracy of weather sources is the biggest barrier preventing the use of weather information.

3) One barrier to using private services and RWIS is the cost. For RWIS, the design and installation as well as communications are the highest cost components. Design and installation are one-time costs, however, and ongoing costs are perceived to be much smaller. The majority of the post-installation costs are related to maintenance. Survey responses indicated that the percentage of winter maintenance budgets spent on obtaining weather information is relatively low (less than 1 percent or between 1 and 5 percent).

4) Air temperature, wind, and the type and amount of precipitation are primary parameters of current and forecast weather conditions. Road weather elements such as pavement temperature, bridge temperature, and pavement conditions are also widely used in winter maintenance. In addition to these, winter maintenance personnel are highly concerned with forecasts of the onset, conclusion, intensity, and duration of storm events. The importance

of weather forecasts decreases with the scale of time from nowcasts to short-term, medium-term, and long-term forecasts.

5) The most noticeable benefit of using weather information for winter maintenance is reducing maintenance cost. The perception that using weather information could save on staffing, materials/chemicals and equipment costs was more likely to be reported by maintenance managers than by field crews/supervisors.

6) Survey results revealed that plowing, deicing, and anti-icing were widely used by survey respondents, and that the employment of anti-icing in winter maintenance is anticipated to increase. Weather information is important in supporting a variety of winter maintenance operations; however, respondents reported needing more weather information to support anti-icing and plowing/de-icing than to support sanding/grit operations. Together, these findings suggest that the demand for weather information among winter maintenance personnel will increase in the future.

7) Survey results showed that maintenance personnel relied less on forecast weather parameters than information on current conditions. Current road and weather parameters of interest included pavement temperature, air temperature, pavement surface condition, precipitation rate, precipitation occurrence, wind speed and direction, and humidity/dew point. Forecast road and weather parameters of interest included the onset/end time of precipitation, precipitation type and amount, pavement temperature trends, and pavement surface condition.

8) The use of weather information varied among the three case study states. The average frequency values of using RWIS and private weather forecasts were 2.75 (Iowa), 3.49 (Nevada), and 1.77 (Michigan). The differences among the states might have been due to their levels of trust in weather information services (e.g., accuracy) and associated service costs.

9) Compared with frequency, the average accuracies of weather information among the states had smaller variations, ranging from 3.4 to 3.6. (Accuracy takes the values of 1 to 5. A value of 3 means that the accuracy of fee-based weather information services is the same as a free weather service; the higher the value, the better.) The survey results indicated that fee-based weather information was more accurate than free weather services, especially for the Iowa and Nevada cases.

10) The case studies found that weather information use had positive effects on winter maintenance costs. Case studies collectively showed that winter maintenance costs decreased as the use of weather information increased or its accuracy improved.

11) It was found that accuracy had a greater effect on maintenance costs than frequency. In other words, winter maintenance costs were more sensitive to weather information accuracy than to the frequency of its use. Hence, the improvement of weather information accuracy is critical to achieving more savings in winter maintenance.

12) The benefit–cost analyses showed that the use of weather information could bring more benefits than costs. The benefits and costs associated with weather information are summarized in the following table. The Michigan case had the highest benefit–cost ratio due to low costs in weather service. However, the percentages of benefits over total winter maintenance costs were 5.6 percent (Iowa), 6.5 percent (Nevada), and 0.9 percent (Michigan). Although the Michigan case had the highest benefit–cost ratio, the percentage of benefits over total winter maintenance costs is the lowest. For this reason, benefit–cost numbers in this research study cannot tell the whole story. Actually, the benefit–cost ratios of the Iowa and Nevada cases are more representative numbers because the costs associated with weather information in these two states were based on statewide numbers, while the Michigan case was not. Please note that the amortized RWIS capital costs were excluded when calculating the cost of weather information for winter maintenance, considering that such costs are often covered by construction projects and the benefits of RWIS are well beyond the winter maintenance community. The in-house equipment and personnel costs related to RWIS maintenance were also excluded since they are often considered to be part of other ITS (intelligent transportation systems) and/or operations costs and hard to track down. The cost of maintaining RWIS sensors, however, were included as part of the maintenance contract. For some agencies, it may be deemed necessary to include some of the abovementioned costs in the total cost of weather information for winter maintenance.

Table 33: Summary of Benefit–Cost Analysis

Case Study State	Winter Season	Winter maintenance Cost ($ 000s)	Benefits ($ 000s)	Weather Information Costs ($ 000s)	Benefit-Cost Ratio	Benefits/ Maintenance Costs (%)
Iowa	2006–07	14,634	814	448	1.8	5.6
Nevada	2006–07	8,924	576	181	3.2	6.5
Michigan	2007–08	31,530	272	7.4	36.7	0.9

13) The benefit–cost analysis only considered agency benefits and did not include benefits to motorists and society. The case studies show that the use of weather information is able to reduce resource usage, which in turn can reduce degradation of the surrounding environment, corrosion effects on motor vehicles, and infrastructure damage. In addition, it will benefit motorists with reduced delay and improved safety as the road surface returns to a normal condition more quickly.

14) Weather information from RWIS is mainly used by maintenance personnel, but it can be also useful to other users. The study identified potential RWIS extensions as well as associated benefits and costs. RWIS has been widely used in many applications such as weather-responsive operations, dynamic warning systems, anti-icing spraying systems, and traveler information systems. Information provided by RWIS can improve accessibility of information, reduce vehicle crashes and crash severity, help travelers develop better trip planning, provide more comfortable driving and so on.

8.2 Recommendations

1) A variety of weather sources can provide useful weather information for winter maintenance. It is recommended that a state DOT identify the resources that can be used within the state. A comparison of the sources (e.g., accuracy, ease of access, cost) may be conducted to rank the sources and provide recommendations.

2) Use of accurate weather information in winter maintenance is critical to reducing costs. The accuracy of weather information, however, is usually limited by the availability of weather sources, budget, and weather detection and forecasting technologies. Thus, it is recommended that state DOTs use the most accurate weather sources for winter maintenance within budget limits and other constraints.

3) The level of trust in weather information and the frequency of using weather information are interrelated. Increased level of trust will improve the use of weather information and, as a result, save more in winter maintenance. For this reason, it is important to know about the level of trust among winter maintenance personnel towards various weather resources. If accuracy problems exist with fee-based services, provide feedback to service providers to solve problems or find better alternatives.

4) It is also recommended that the use of weather information be more focused towards the road environment. The use of road weather information (e.g., pavement temperature and trend, bridge temperature) is important information for developing better maintenance strategies.

5) The case studies collectively showed that winter maintenance costs decreased with the increase use of weather information or accuracy. As such, the maintenance agencies should continue to invest in road weather information with high accuracy (such as RWIS and customized weather service) and to ensure high usage of the existing road weather information services. One way to boost the user acceptance and to increase the usage of weather information would be through training along with close communication of weather service providers and winter maintenance practitioners. It is also recommended that agencies leverage existing infrastructure (e.g. existing ITS sites with available power and communications) when choosing RWIS installation sites to help reduce costs.

APPENDIX A: GLOSSARY OF ACRONYMS

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
AMS	American Meteorological Society
ANN	Artificial Neural Network
ASOS	Automated Surface Observing System
ATWIS	Advanced Transportation Weather Information System
AWI	All Weather Inc.
AWOS	Automated Weather Observing System
BPNN	Back-propagation Neural Network
CCTV	Closed Circuit Television
CGI	Common Gateway Interface
COATS	California/Oregon Advanced Transportation Systems
CPU	Communication Processing Unit
DMS	Dynamic Message Sign
DOT	Department of Transportation
DSRC	Dedicated Short Range Communications
DSS	Decision Support System
ESS	Environmental sensing stations
FAA	Federal Aviation Administration
FAST	Fixed Automated Spray Technology
FCMSSR	Federal Coordinator for Meteorological Services and Supporting Research
FHWA	Federal Highway Administration
GPS	Global Positioning System
HCM	Highway Capacity Manual
ITS	Intelligent Transportation Systems
JPO	Joint Program Office
lbs/l-m	Pounds per lane-mile
LDTI	Limited Deployment Tactical Integration
LOS	Level of Service
MDSS	Maintenance Decision Support System
MOS	Model Output Statistics

MSE	Mean Square Error
NCDC	National Climatic Data Center
NDFD	National Digital Forecast Database
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NWS	National Weather Service
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
RPU	Remote Processing Units
RWIS	Road Weather Information System
SHRP	Strategic Highway Research Program
STWDSR	Surface Transportation Weather Decision Support Requirements
THREDDS	Thematic Real-time Environmental Distributed Data Services
TMC	Traffic Management Center
TOC	Traffic Operations Center
TRIS	Transportation Research Information Service
VAMS	Value-Added Meteorological Services
VII	Vehicle Infrastructure Integration
VMT	Vehicle Miles Traveled
VSL	Variable Speed Limit
WIST	Weather Information for Surface Transportation
WMS	Web Map Service
WRS	Weather Response System

APPENDIX B: WEB-BASED SURVEY

Hello:
The Aurora Program has contracted with the Western Transportation Institute to conduct a project quantifying the benefits and costs associated with using various sources of weather information in winter maintenance. As a part of the research project, this survey is designed to learn from practitioners from across the United States and Canada about their experiences in using weather information in winter maintenance.

We would appreciate it if you would take a few minutes to complete this survey. Please answer these questions from the perspective of your current position and area of geographic responsibility.

The survey should take 20-30 minutes to complete. You may start the survey now and complete it later if it's more convenient for you. Please try to complete the survey by **Friday, September 7**.

If you have any questions or need clarification on this survey, please contact Chris Strong of WTI at ChrisS@coe.montana.edu, or at 406-994-7351.

Thank you for your participation.

Questions about You

*** 1. Please indicate the type of organization you work for.**

- ◯ State or provincial transportation agency (incl. toll facilities)
- ◯ County/municipal transportation agency
- ◯ Private-sector winter maintenance contractor
- ◯ Private-sector weather information provider
- ◯ Other

*** 2. Please describe your level of responsibility for performing winter maintenance operations. (Please check all that apply.)**

- ☐ Field crew / operator of winter maintenance equipment
- ☐ Supervisor of equipment operators
- ☐ Maintenance manager without direct contact with equipment operators
- ☐ Other (please specify)

*** 3. What state/province do you work in? (If you work outside of the U.S. or Canada, please indicate the country in which you work.)**

4. (Optional) Please provide your e-mail address, in case we need to follow up with you for clarification on your responses.

Questions on Your Winter Maintenance Context

*** 5. What kind of winter weather does your area typically experience? (Please select one frequency for each type of winter weather.)**

	Never	Seldom	Once per year	A couple of times per year	Several times per year
Extreme low temperatures (sustained temperatures below 15° F/-10° C)	○	○	○	○	○
Freezing rain	○	○	○	○	○
Snow storms	○	○	○	○	○
Surface ice/frost	○	○	○	○	○
Wind (sustained speeds over 15 mph/24 kmph)	○	○	○	○	○

*** 6. How often do the following people in your organization consult weather information sources for winter maintenance operations? (Please select one for each organizational level.)**

	Never	When a storm is imminent	Most winter days	Daily	Several times per day	Don't Know
Field Crews	○	○	○	○	○	○
Crew Supervisors	○	○	○	○	○	○
Maintenance Managers	○	○	○	○	○	○

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*** 7. How often did you use *Free Weather Information Sources* for weather information to support winter maintenance operations last winter?**

***Free Weather Information Sources* refer to sources of weather information which are available to the general public without paying a subscription or per-use fee. These include the National Weather Service/NOAA, local television and radio, national or cable TV broadcasts, and free weather information web sites (e.g. http://www.weather.com/, http://www.wunderground.com/, http://www.cnn.com/).**

- ○ Never
- ○ Seldom (Couple of Times Per Season)
- ○ Sometimes (Couple of Times Per Week)
- ○ Often (Daily)
- ○ Always (Multiple Times Per Day)

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*** 8. For which parameters about CURRENT weather conditions do you consult *Free Weather Information Sources*? Please check all that apply.**

- [ ] Do not use for current conditions
- [ ] Air temperature
- [ ] Relative humidity/dewpoint
- [ ] Pavement temperature
- [ ] Pavement condition
- [ ] Bridge temperature
- [ ] Wind
- [ ] Visibility
- [ ] Precipitation amount and type
- [ ] Other (please specify)

*** 9. For which parameters about FORECAST weather conditions do you consult *Free Weather Information Sources*? Please check all that apply.**

- [ ] Do not use for forecasts
- [ ] Air temperature trends
- [ ] Relative humidity/dewpoint
- [ ] Pavement temperature trends
- [ ] Pavement condition
- [ ] Frost forecasts
- [ ] Bridge temperature
- [ ] Wind/blowing snow
- [ ] Visibility
- [ ] Precipitation amount and type
- [ ] Timing/onset of the weather event
- [ ] Intensity and duration of the weather event
- [ ] Exit timing of the weather event
- [ ] Other (please specify)

*** 10. How satisfied are you with *Free Weather Information Sources* as a weather information source?**

- ( ) Very satisfied
- ( ) Satisfied
- ( ) Neutral
- ( ) Dissatisfied
- ( ) Very dissatisfied

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*** 11. Select the time scale(s) for which you use weather FORECASTS from *Free Weather Information Sources*.**

- [ ] Nowcast (1-6 hrs)
- [ ] Short-term (6-24 hrs)
- [ ] Medium-term (24 hr-5 day)
- [ ] Long-term (more than 5 days)

Use of Weather Information Sources, p. 4 of 16

*** 12. How often did you use *Private-Sector Weather Information Providers* for weather information to support winter maintenance operations last winter?**

***Private-Sector Weather Information Providers* refers to for-fee services by which the private sector provides customized weather information (typically forecasts) to an agency. The fees are typically based on an annual subscription as opposed to a per-use payment. This may be available as a restricted access web site, an e-mail alert, satellite feeds, or other methods.**

This information source is different from RWIS and Decision Support Systems, each of which is covered later.

- ( ) Never
- ( ) Seldom (Couple of Times Per Season)
- ( ) Sometimes (Couple of Times Per Week)
- ( ) Often (Daily)
- ( ) Always (Multiple Times Per Day)

Use of Weather Information Sources, p. 5 of 16

*** 13. For which parameters about CURRENT weather conditions do you consult *Private-Sector Weather Information Providers*? Please check all that apply.**

- [ ] Do not use for current conditions
- [ ] Air temperature
- [ ] Relative humidity/dewpoint
- [ ] Pavement temperature
- [ ] Pavement condition
- [ ] Bridge temperature
- [ ] Wind
- [ ] Visibility
- [ ] Precipitation amount and type
- [ ] Other (please specify)

*** 14. For which parameters about FORECAST weather conditions do you consult *Private-Sector Weather Information Providers*? Please check all that apply.**

- [ ] Do not use for forecasts
- [ ] Air temperature trends
- [ ] Relative humidity/dewpoint
- [ ] Pavement temperature trends
- [ ] Pavement condition
- [ ] Frost forecasts
- [ ] Bridge temperature
- [ ] Wind/blowing snow
- [ ] Visibility
- [ ] Precipitation amount and type
- [ ] Timing/onset of the weather event
- [ ] Intensity and duration of the weather event
- [ ] Exit timing of the weather event
- [ ] Other (please specify)

*** 15. How satisfied are you with *Private-Sector Weather Information Providers* as a weather information source?**

- ( ) Very satisfied
- ( ) Satisfied
- ( ) Neutral
- ( ) Dissatisfied
- ( ) Very dissatisfied

Use of Weather Information Sources, p. 6 of 16

*** 16. Select the time scale(s) for which you use weather FORECASTS from *Private-Sector Weather Information Providers*.**

- [ ] Nowcast (1-6 hrs)
- [ ] Short-term (6-24 hrs)
- [ ] Medium-term (24 hr-5 day)
- [ ] Long-term (more than 5 days)

Use of Weather Information Sources, p. 7 of 16

*** 17. How often did you use *RWIS* for weather information to support winter maintenance operations last winter?**

An *RWIS* (road weather information system) is an integrated suite of weather and pavement sensors that are used to measure current weather conditions at the road environment, and transmit this information on a real-time basis.

- ◯ Never
- ◯ Seldom (Couple of Times Per Season)
- ◯ Sometimes (Couple of Times Per Week)
- ◯ Often (Daily)
- ◯ Always (Multiple Times Per Day)

Use of Weather Information Sources, p. 8 of 16

*** 18. For which parameters about CURRENT weather conditions do you consult *RWIS*? Please check all that apply.**

- ☐ Air temperature
- ☐ Relative humidity/dewpoint
- ☐ Pavement temperature
- ☐ Pavement condition
- ☐ Bridge temperature
- ☐ Wind
- ☐ Visibility
- ☐ Precipitation amount and type
- ☐ Other (please specify)

*** 19. How satisfied are you with *RWIS* as a weather information source?**

- ◯ Very satisfied
- ◯ Satisfied
- ◯ Neutral
- ◯ Dissatisfied
- ◯ Very dissatisfied

Use of Weather Information Sources, p. 9 of 16

*** 20. How often did you use *Road Weather Mesonets* for weather information to support winter maintenance operations last winter?**

***Road weather mesonets* combine current weather observations from a variety of sources into a single interface, and often have internal quality control algorithms. Examples of systems providing this type of weather information include Washington State's rWeather, Iowa's WeatherView, California's WeatherShare and the Clarus Initiative.**

- ◯ Never
- ◯ Seldom (Couple of Times Per Season)
- ◯ Sometimes (Couple of Times Per Week)
- ◯ Often (Daily)
- ◯ Always (Multiple Times Per Day)

Use of Weather Information Sources, p. 10 of 16

*** 21. For which parameters about CURRENT weather conditions do you consult *Road Weather Mesonets*? Please check all that apply.**

- ☐ Air temperature
- ☐ Relative humidity/dewpoint
- ☐ Pavement temperature
- ☐ Pavement condition
- ☐ Bridge temperature
- ☐ Wind
- ☐ Visibility
- ☐ Precipitation amount and type
- ☐ Other (please specify)

*** 22. How satisfied are you with *Road Weather Mesonets* as a weather information source?**

- ◯ Very satisfied
- ◯ Satisfied
- ◯ Neutral
- ◯ Dissatisfied
- ◯ Very dissatisfied

Use of Weather Information Sources, p. 11 of 16

*** 23. How often did you use *Decision Support Systems* for weather information to support winter maintenance operations last winter?**

***Decision Support Systems* are systems which integrate information about current conditions with weather forecasts to provide improved guidance to support winter maintenance decisions.**

One example of a decision support system is MDSS (Maintenance Decision Support System). MDSS is a computer tool which integrates current and forecast weather information, with information on current roadway conditions, to provide the user with recommendations for the most appropriate winter maintenance treatment for a given highway.

Another example is FORETELL, a multi-state advanced road and weather condition prediction system that integrates satellite, radar and surface observations with RWIS data, using state-of-the-art weather models and decision support displays.

- ◯ Never
- ◯ Seldom (Couple of Times Per Season)
- ◯ Sometimes (Couple of Times Per Week)
- ◯ Often (Daily)
- ◯ Always (Multiple Times Per Day)

Use of Weather Information Sources, p. 12 of 16

*** 24. For which parameters about CURRENT weather conditions do you consult *Decision Support Systems*? Please check all that apply.**

- ☐ Do not use for current conditions
- ☐ Air temperature
- ☐ Relative humidity/dewpoint
- ☐ Pavement temperature
- ☐ Pavement condition
- ☐ Bridge temperature
- ☐ Wind
- ☐ Visibility
- ☐ Precipitation amount and type
- ☐ Other (please specify)

*** 25. For which parameters about FORECAST weather conditions do you consult *Decision Support Systems*? Please check all that apply.**

- [ ] Do not use for forecasts
- [ ] Air temperature trends
- [ ] Relative humidity/dewpoint
- [ ] Pavement temperature trends
- [ ] Pavement condition
- [ ] Frost forecasts
- [ ] Bridge temperature
- [ ] Wind/blowing snow
- [ ] Visibility
- [ ] Precipitation amount and type
- [ ] Timing/onset of the weather event
- [ ] Intensity and duration of the weather event
- [ ] Exit timing of the weather event
- [ ] Other (please specify)

*** 26. How satisfied are you with *Decision Support Systems* as a weather information source?**

- ○ Very satisfied
- ○ Satisfied
- ○ Neutral
- ○ Dissatisfied
- ○ Very dissatisfied

Use of Weather Information Sources, p. 13 of 16

*** 27. Select the time scale(s) for which you use weather FORECASTS from *Decision Support Systems*.**

- [ ] Nowcast (1-6 hrs)
- [ ] Short-term (6-24 hrs)
- [ ] Medium-term (24 hr-5 day)
- [ ] Long-term (more than 5 days)

Use of Weather Information Sources, p. 14 of 16

*** 28. Do you use any sources for weather information that have not been identified previously?**

- ○ Yes
- ○ No

Use of Weather Information Sources, p. 15 of 16

*** 29. Please list any other source(s) you use for weather information beyond those that were already mentioned.**

*** 30. Describe what you use this information source for (ex. current conditions, forecasts; the types of parameters of interest).**

*** 31. How satisfied are you with the source you just mentioned as a weather information source?**

- ◯ Very satisfied
- ◯ Satisfied
- ◯ Neutral
- ◯ Dissatisfied
- ◯ Very dissatisfied

Use of Weather Information Sources, p. 16 of 16

*** 32. For each source of weather information, please indicate whether you foresee using each particular source LESS or MORE FREQUENTLY in the future. Please select one circle per row.**

	Less Frequently	No Change	More Frequently
Free Weather Information Sources (e.g. NWS, TV/radio, Internet)	◯	◯	◯
Private-Sector Weather Information Providers	◯	◯	◯
RWIS	◯	◯	◯
Road Weather Mesonets	◯	◯	◯
Decision Support Systems	◯	◯	◯
Other	◯	◯	◯

33. In general, in which ways do each of these weather information sources influence your approach to winter maintenance operations? Please check a box for each information source that influences a particular aspect of your winter maintenance operations.

	Free Weather Information Sources	Private-Sector Weather Information Sources	RWIS	Road Weather Mesonets	Decision Support Systems	Other
Application of anti-icing	☐	☐	☐	☐	☐	☐
Usage of pre-treatment	☐	☐	☐	☐	☐	☐
Usage of chemicals and materials	☐	☐	☐	☐	☐	☐
Frequency of ice/snow plowing	☐	☐	☐	☐	☐	☐
Frequency of patrolling	☐	☐	☐	☐	☐	☐
Amount of overtime work	☐	☐	☐	☐	☐	☐

34. Please rank the most important types of weather information for each time scale (1 = most important, etc.). Please rank no more than five for each time scale.

A *weather discussion* is a narrative that provides general context for the current conditions or forecast. For example, "A strong winter storm should be rolling in late Thursday night, with heavy wet snow and blowing winds."

	Current Observations	Forecast (1-6 hours out)	Forecast (6-24 hours out)	Forecast (24 hours-5 days out)	Forecast (More than 5 days out)
Pavement temperature					
Pavement surface condition					
Chemical concentration					
Wind speed and direction					
Air temperature/ trends					
Dew point and humidity					
Solar radiation/cloud cover					
Pressure					
Visibility					
Precipitation amount					
Precipitation begin/end time					
Precipitation type					
Weather discussion					

Winter Maintenance Operations, p. 1 of 5

*** 35. Do you currently use *Anti-Icing* as part of your winter maintenance operations?**

***Anti-icing* is a pro-active snow and ice control strategy to prevent bond formation between ice and pavement surfaces. (Definition provided by Washington State Dept. of Transportation.)**

- ◯ Yes
- ◯ No

*** 36. How do you foresee the frequency of your usage of *Anti-Icing* changing in the future?**

- ◯ Less frequently
- ◯ No change
- ◯ More frequently

37. Which types of CURRENT weather information do you use, or would you use, in supporting *Anti-Icing* operations?

	Use	Do not use, but would use if available
Pavement temperature	◯	◯
Pavement surface condition	◯	◯
Chemical concentration	◯	◯
Wind speed and direction	◯	◯
Air temperature	◯	◯
Dewpoint and humidity	◯	◯
Solar radiation/cloud cover	◯	◯
Pressure	◯	◯
Precipitation occurrence	◯	◯
Precipitation rate	◯	◯
Precipitation type	◯	◯
Don't know	◯	◯

Other (please specify)

38. Which types of FORECAST weather information do you use, or would you use, in supporting *Anti-Icing* operations?

	Use	Do not use, but would use if available
Pavement temperature trends	○	○
Pavement surface condition	○	○
Chemical concentration	○	○
Wind speed and direction	○	○
Air temperature trends	○	○
Dewpoint and humidity	○	○
Solar radiation/cloud cover	○	○
Pressure	○	○
Precipitation amount	○	○
Precipitation begin/end time	○	○
Precipitation type	○	○
Don't know	○	○

Other (please specify)

Winter Maintenance Operations, p. 2 of 5

*** 39. Do you currently use *Plowing* or *Deicing* as part of your winter maintenance operations?**

***Plowing* and *Deicing* are reactive strategies which seeks to break the bond between already bonded snow and ice and the roadway surface.**

○ Yes
○ No

*** 40. How do you foresee the frequency of your usage of *Plowing* or *Deicing* changing in the future?**

○ Less frequently
○ No change
○ More frqeuently

41. Which types of CURRENT weather information do you use, or would you use, in supporting *Plowing* or *Deicing* operations?

	Use	Do not use, but would use if available
Pavement temperature	◯	◯
Pavement surface condition	◯	◯
Chemical concentration	◯	◯
Wind speed and direction	◯	◯
Air temperature	◯	◯
Dewpoint and humidity	◯	◯
Solar radiation/cloud cover	◯	◯
Pressure	◯	◯
Precipitation occurrence	◯	◯
Precipitation rate	◯	◯
Precipitation type	◯	◯
Don't know	◯	◯

Other (please specify)

42. Which types of FORECAST weather information do you use, or would you use, in supporting *Plowing* or *Deicing* operations?

	Use	Do not use, but would use if available
Pavement temperature trends	◯	◯
Pavement surface condition	◯	◯
Chemical concentration	◯	◯
Wind speed and direction	◯	◯
Air temperature trends	◯	◯
Dewpoint and humidity	◯	◯
Solar radiation/cloud cover	◯	◯
Pressure	◯	◯
Precipitation amount	◯	◯
Precipitation begin/end time	◯	◯
Precipitation type	◯	◯
Don't know	◯	◯

Other (please specify)

Winter Maintenance Operations, p. 3 of 5

*** 43. Do you currently use *Sanding / Grit Application* as part of your winter maintenance operations?**

- ◯ Yes
- ◯ No

*** 44. How do you foresee the frequency of your usage of *Sanding / Grit Application* changing in the future?**

- ◯ Less frequently
- ◯ No change
- ◯ More frqeuently

45. Which types of CURRENT weather information do you use, or would you use, in supporting *Sanding / Grit Application* operations?

	Use	Do not use, but would use if available
Pavement temperature	◯	◯
Pavement surface condition	◯	◯
Chemical concentration	◯	◯
Wind speed and direction	◯	◯
Air temperature	◯	◯
Dewpoint and humidity	◯	◯
Solar radiation/cloud cover	◯	◯
Pressure	◯	◯
Precipitation occurrence	◯	◯
Precipitation rate	◯	◯
Precipitation type	◯	◯
Don't know	◯	◯

Other (please specify)

46. Which types of FORECAST weather information do you use, or would you use, in supporting *Sanding / Grit Application* operations?

	Use	Do not use, but would use if available
Pavement temperature trends	○	○
Pavement surface condition	○	○
Chemical concentration	○	○
Wind speed and direction	○	○
Air temperature trends	○	○
Dewpoint and humidity	○	○
Solar radiation/cloud cover	○	○
Pressure	○	○
Precipitation amount	○	○
Precipitation begin/end time	○	○
Precipitation type	○	○
Don't know	○	○

Other (please specify)

Winter Maintenance Operations, p. 4 of 5

*** 47. Are there any other winter maintenance operations that your agency performs for which weather information is critical?**

○ Yes
○ No

Winter Maintenance Operations, p. 5 of 5

*** 48. Please describe/define this winter maintenance operation.**

*** 49. How do you foresee the frequency of your usage of this type of operation changing in the future?**

○ Less frequently
○ No change
○ More frqeuently

50. Which types of CURRENT weather information do you use, or would you use, in supporting this type of winter maintenance operation?

	Use	Do not use, but would use if available
Pavement temperature	◯	◯
Pavement surface condition	◯	◯
Chemical concentration	◯	◯
Wind speed and direction	◯	◯
Air temperature	◯	◯
Dewpoint and humidity	◯	◯
Solar radiation/cloud cover	◯	◯
Pressure	◯	◯
Precipitation occurrence	◯	◯
Precipitation rate	◯	◯
Precipitation type	◯	◯
Don't know	◯	◯

Other (please specify)

51. Which types of FORECAST weather information do you use, or would you use, in supporting this type of winter maintenance operation?

	Use	Do not use, but would use if available
Pavement temperature trends	◯	◯
Pavement surface condition	◯	◯
Chemical concentration	◯	◯
Wind speed and direction	◯	◯
Air temperature trends	◯	◯
Dewpoint and humidity	◯	◯
Solar radiation/cloud cover	◯	◯
Pressure	◯	◯
Precipitation amount	◯	◯
Precipitation begin/end time	◯	◯
Precipitation type	◯	◯
Don't know	◯	◯

Other (please specify)

Costs of Weather Information

*** 52. What percentage of your total winter maintenance cost was spent in getting weather information last winter? Please include all costs associated with weather information, including cost of private forecasting services, RWIS design and construction, RWIS operations and maintenance, etc. Please select one.**

- ◯ Less than 1%
- ◯ 1-5%
- ◯ 5-10%
- ◯ 10-20%
- ◯ More than 20%
- ◯ Don't know

Please explain your estimate of the relative cost of weather information

53. Please rank the following cost components of weather information from 1 as the most expensive to 5 as the least expensive. (If you do not know, please leave this question blank.)

Interpreting Forecasts **refers to the cost involved in taking a traditional weather forecast and translating it into information that could be used to direct winter maintenance decisions. This may include tools such as private-sector weather information services and decision support systems.**

Designing and Installing RWIS	
Communications to RWIS	
Maintenance of RWIS	
Obtaining Forecasts	
Interpreting Forecasts	

*** 54. In general, how has weather information affected your winter maintenance costs in each of these categories? Please select one per row.**

	Increased greatly	Increased	No change	Decreased	Decreased greatly	Don't know
Staffing	◯	◯	◯	◯	◯	◯
Chemicals / Materials	◯	◯	◯	◯	◯	◯
Equipment	◯	◯	◯	◯	◯	◯

Assessment of Weather Information

*** 55. Out of the following list, please select and rank the top three most needed improvements in weather information for winter maintenance. (1 = most needed improvement, 2 = second-most needed improvement, 3 = third-most needed improvement)**

More timely forecasts	
Improved access to a forecaster	
Improved proactive warning of storm conditions (e.g. e-mail, pager alerts)	
Better knowledge of pavement temperatures	
Better forecasts about precipitation timing, type and amount	

*** 56. What barriers prevent your agency from using weather information more frequently to assist you in your winter maintenance operations? Please rank the top three barriers (1 = biggest barrier, 2 = second biggest barrier, 3 = third biggest barrier).**

	Rank of Barrier
The information sources that we want to use (e.g. private-sector, RWIS) would cost too much.	
I don't have data on the benefits we can achieve through investing in weather information products and services.	
The weather information we receive is not trustworthy.	
The weather information available to us doesn't give us sufficient detail to help determine winter maintenance actions (e.g. it doesn't specify storm event timing)	
We have communications challenges with our weather information sources, so information can not be interpreted into directions in time.	

Weather information is not trustworthy enough to introduce changes in winter maintenance operations.	
I don't know how to use all of the weather information I receive.	
The weather conditions and road surface conditions are quite consistent, so forecasting is not so necessary.	
There are liability concerns if we acquire more or better weather information.	
Other (specify in box below)	

Please specify.

*** 57. What are the benefits that your agency would realize from using the weather information for winter maintenance? Please rank the top three benefits (1 = biggest benefit, 2 = second biggest benefit, 3 = third biggest benefit).**

	Rank of Benefit
More timely and accurate response to winter storms	
Better preparation for storms, including scheduling of crews and preparation of equipment	
More accurate staffing and budget plans for an entire season	
Reduced usage of chemicals and materials	
Reduced labor costs, including overtime	
Reduced equipment usage and associated costs	
Improved roadway clearance time	
Other (specify in box below)	

Please specify.

58. Has your agency conducted a benefit-cost analysis of the use of weather information? If so, please provide information that could help us to locate this study.

Comments

59. Please provide any other comments you may have regarding your use of weather information to support winter maintenance.

APPENDIX C: QUESTIONNAIRE FOR OUTREACH TO METEOROLOGICAL COMMUNITY

1. How long have you been involved with providing services to the surface transportation (highway) community?
2. Do you have any users within the winter highway maintenance community (i.e. people who are responsible for treating and clearing roads during the winter months)?
   a. Are your users primarily public sector or private sector?
   b. What are the scales of geographic responsibility (i.e. statewide, regional)?
   c. What are their levels of organizational responsibility?
   d. What time frames of information are they interested in?
   e. How do you understand they apply the weather information you provide?
3. Do you provide customized weather observational services (i.e. data on current conditions) to the surface transportation (highway) community?
   a. What is your geographic expanse of coverage? Nationwide, or certain parts of the country?
   b. What is the geographic detail of coverage?
   c. What types of data do you provide?
   d. How do you typically provide information (e.g. e-mail, telephone, secure web site)?
   e. Are these services provided for a fee? In general, how is the fee established? What is a typical range of fees that might be associated with a state transportation agency?
   f. Do you limit who uses the information you provide (e.g. limited number of "seats")? If so, how?
4. Do you provide customized weather forecasting services to the surface transportation (highway) community?
   a. What is your geographic expanse of coverage? Nationwide, or certain parts of the country?
   b. What is the geographic detail of coverage?
   c. What types of data do you forecast?
   d. For time horizons do you provide forecasts?
   e. How do you typically provide information (e.g. e-mail, telephone, secure web site)?
   f. Are these services provided for a fee? In general, how is the fee established? What is a typical range of fees that might be associated with a state transportation agency?
   g. Do you limit who uses the information you provide (e.g. limited number of "seats")? If so, how?
5. What factors do you see as encouraging transportation agencies in pursuing customized weather information services?
6. What factors do you see as discouraging transportation agencies from pursuing customized weather information services?
7. Please assess, qualitatively, the benefits and costs of weather information services that you currently provide to winter maintenance community.
8. We want to get a thorough representation of the meteorological community's perspectives on the use of weather information in winter maintenance. Are there other firms or agencies that we should contact for additional insight on these questions?

APPENDIX D: WEATHER USE INFORMATION SURVEY QUESTIONNAIRE

Title Page

Hello:
The Aurora Program has contracted with the Western Transportation Institute to quantify the benefits and costs associated with using various sources of weather information in winter maintenance.

The purpose of this brief survey is to determine the extent to which your maintenance area uses weather information to support winter maintenance decisions. The results of this survey will be used to help determine if the weather information you use is cost-effective.

Please complete this survey based on your usage of weather information during **this past winter season** (2007-08).

The survey should take 5-10 minutes to complete. You may start the survey now and complete it later if it's more convenient for you. Please try to complete the survey by **Friday, April 30**.

If you have any questions or need clarification on this survey, please contact Xianming Shi of WTI at Xianming_S@coe.montana.edu, or at 406-994-6486.

Thank you for your participation.

Demographic / Classification Info

*** 1. Please select your title.**

- ☐ Circle Supervisor
- ☐ E.O. Senior or GOA
- ☐ Other

*** 2. If you are a circle supervisor, please enter the cost center numbers under your supervision. If you are a E.O. Senior or GOA, please enter your cost center number.**

3. (Optional) Please enter your e-mail address.

Do You Use RWIS/ESS?

*** 4. Do you use roadside weather stations (aka RWIS/ESS) for your winter maintenance operations?**

RWIS/ESS **refers to a set of environment sensors used to measure current weather conditions. It includes the capability to measure weather parameters such as air temperature, wind speed and direction, and pavement temperature.**

- ○ Yes
- ○ No

*** 5. Do you have an RWIS site located within your geographic area of responsibility?**

- ○ Yes
- ○ No

RWIS/ESS

*** 6. How often do you consult RWIS/ESS during the winter?**

- ◯ More than once per day (more frequent when storms are forecast or occurring)
- ◯ Daily
- ◯ Less than daily, and only when storms are forecast or occurring

*** 7. How much do you agree with each of the following statements? Please check one rating for each statement.**

	1 Strongly Disagree	2 Disagree	3 Neither Agree nor Disagree	4 Agree	5 Strongly Agree
It is easy to access or view the RWIS/ESS data.	◯	◯	◯	◯	◯
RWIS/ESS weather data (e.g. air temperature, precipitation, pavement temperature) are very accurate.	◯	◯	◯	◯	◯

If you rated the accuracy as less than 3, please list the sensors which tend to be most inaccurate.

Frequency of Use of DTN Forecasts

*** 8. How often do you use <u>DTN Forecasts</u> during the winter?**

- ◯ More than once per day (more frequent when storms are forecasted or occurring)
- ◯ Daily
- ◯ Less than daily, and only when storms are forecast or occurring
- ◯ Never

DTN Forecasts

*** 9. Please rate the accuracy of DTN forecasts <u>in comparison to</u> free weather information providers, such as the National Weather Service or free Internet sites.**

	1 Much less accurate	2	3 Equally accurate	4	5 Much more accurate
Nowcasts (less than 6 hours into the future)	◯	◯	◯	◯	◯
Short-term (6-24 hours into the future)	◯	◯	◯	◯	◯
Medium-term (1-5 days into the future)	◯	◯	◯	◯	◯
Long-term (more than 5 days into the future)	◯	◯	◯	◯	◯

*** 10. How relevant (in terms of quality, timeliness, accessibility, and geographic specificity of forecasting services) are DTN forecasts compared to free services, e.g. National Weather Service?**

- ◯ 5 - Much more relevant
- ◯ 4 - More relevant
- ◯ 3 - Equally relevant
- ◯ 2 - Less relevant
- ◯ 1 - Much less relevant

*** 11. How much interaction do you have with DTN forecasters? Check all that apply.**

- ☐ The forecaster helps me interpret the forecasts so I know how to act on them
- ☐ I provide feedback to the forecaster regarding forecast quality
- ☐ I have no interaction with the forecaster

Frequency of Use of Meridian Road Weather Forecasts

*** 12. How often do you use Meridian road weather forecasts during the winter?**

- ◯ More than once per day (more frequent when storms are forecast or occurring)
- ◯ Daily
- ◯ Less than daily, and only when storms are forecast or occurring
- ◯ Never

Meridian

*** 13. Please rate the accuracy of Meridian in comparison to free weather information providers, such as the National Weather Service or free Internet sites.**

	1 Much less accurate	2	3 Equally accurate	4	5 Much more accurate
Nowcasts (less than 6 hours into the future)	◯	◯	◯	◯	◯
Short-term (6-24 hours into the future)	◯	◯	◯	◯	◯
Medium-term (1-5 days into the future)	◯	◯	◯	◯	◯
Long-term (more than 5 days into the future)	◯	◯	◯	◯	◯

*** 14. How relevant (in terms of quality, timeliness, accessibility, and geographic specificity of forecasting services) are Meridian's road weather forecasts compared to free services, e.g. National Weather Service?**

- ◯ 5 - Much more relevant
- ◯ 4 - More relevant
- ◯ 3 - Equally relevant
- ◯ 2 - Less relevant
- ◯ 1 - Much less relevant

*** 15. How much interaction do you have with Meridian forecasters? Check all that apply.**

- ☐ The forecaster helps me interpret the forecasts so I know how to act on them
- ☐ I provide feedback to the forecaster regarding forecast quality
- ☐ I have no interaction with the forecaster

Maintenance Decision Support System (MDSS)

*** 16. How often do you use Maintenance Decision Support System (MDSS) during the winter?**

- ◯ More than once per day (more frequent when storms are forecast or occurring)
- ◯ Daily
- ◯ Less than daily, and only when storms are forecast or occurring
- ◯ Never, although I do have access to it
- ◯ Never, because I don't have access to it

Forecast Provider Preference

*** 17. Which forecasting service do you rely on most during the winter? Please select one for each timeframe. ("Do not use" is an option for each timeframe.)**

	Free services (e.g. National Weather Service)	DTN Forecasts	Meridian	MDSS	Do not use
Nowcasts (less than 6 hours)	◯	◯	◯	◯	◯
Short-term (6-24 hours)	◯	◯	◯	◯	◯
Medium-term (1-5 days)	◯	◯	◯	◯	◯
Long-term (more than 5 days)	◯	◯	◯	◯	◯

Changes in Use of Weather Information

*** 18. Has your circle or cost center changed how it uses the earlier cited weather information sources (e.g. RWIS, MDSS, Meridian, DTN Forecasts) over the last couple of years?**

- ◯ Yes
- ◯ No

If yes, please describe how your use of weather information has changed.

Use of Anti-Icing

*** 19. Please characterize your area's use of anti-icing.**

***Anti-icing* is a pro-active snow and ice control strategy to prevent ice from bonding to the pavement. It involves application of chemicals to the road surface just prior to a snow event.**

- ◯ We never anti-ice
- ◯ We are interested in anti-icing but don't have the right equipment and/or chemicals
- ◯ We are interested in anti-icing but don't have good enough forecasts
- ◯ We regularly employ anti-icing on select routes
- ◯ We regularly employ anti-icing on all eligible routes

Your survey has been accepted!

Thank you for participating in this survey.

APPENDIX E: EXAMPLES OF RESEARCH STUDIES ON THE EFFECTS OF WEATHER ON SAFETY AND SPEED

Authors	Safety Metric	Speed Metric	Pavement Condition Metric	Event [e.g., snowfall] Definition
Kyte, Khatib, Shannon and Kitchener (92)	None	16.4 km/hr reduction in speeds when snow is on road	16.4 km/hr reduction in speeds when snow is on road	Not stated
Knapp, Kroeger and Giese (93)	Analysis 1: Crash rate increases by 1300 percent during storm events (see definition under event) Analysis 2: 1 inch/hour of snow increases number of crashes by 250 percent	Same study was covered in	None	RWIS data: Precip occurring (at least 0.20 inches per hour) Temp below freezing Wet pavement surface (at one or more sensors) Pavement temp below freezing (at all sensors) These conditions must exist for at least four consecutive hours
Kyte, Khatib, Shannon and Kitchener (94)	None	9.1-10.8 km/hr reduction in speeds when snow/ice is present on roadway (from 117 km/hr dry pavement speed)	9.1-10.8 km/hr reduction in speeds when snow/ice is present on roadway (from 117 km/hr dry pavement speed)	Normal speeds calculated on no precipitation, dry roadway, visibility greater than 0.37 km, wind speed less than 16 km/hr
Wallman, C-G (95)	None	Of 14 different pavement conditions, the following were average speed reductions Moist: 1 km/hr Wet: 2 km/hr Hoarfrost: 4 km/hr Black Ice: 5 km/hr Hard snow: 12 km/hr Soft snow: 10 km/hr Slush: 11 km/hr	Of 14 different pavement conditions, the following were average speed reductions Moist: 1 km/hr Wet: 2 km/hr Hoarfrost: 4 km/hr Black Ice: 5 km/hr Hard snow: 12 km/hr Soft snow: 10 km/hr Slush: 11 km/hr	Not defined (not clear how RWIS data was used)

Authors	Safety Metric	Speed Metric	Pavement Condition Metric	Event [e.g., snowfall] Definition
Norrman, Eriksson and Lindqvist (96)	Accident risk, compared to non-slippery surface, increased as follows (see events) (1) - 1557% (2) – 771% (3) – 386% (4) – 814% (5) – 114% (6) – 357% (7) – 257% (8) – 543% (9) – 114% (10) – 271%	None	Accident risk, compared to non-slippery surface, increased as follows (see events) (1) - 1557% (2) – 771% (3) – 386% (4) – 814% (5) – 114% (6) – 357% (7) – 257% (8) – 543% (9) – 114% (10) – 271%	Road conditions classified using an expert system based on RWIS-available variables: (1) Rain/sleet on a frozen road surface (2) Snow on a frozen road surface (3) Snow/sleet on a warm road surface (4) Snowfall plus hoarfrost (5) Hoarfrost plus low visibility (6) Freezing dew followed by hoarfrost (7) Strong hoarfrost (8) Weak hoarfrost (9) Drifting snow (10) Watercover which freezes
Maki (97)	None	Average speed dropped from 44 mph during "normal" to 26 mph during "adverse" conditions	Indirectly	Adverse event is snowstorm with three or more inches of snow
Liang, Kyte, Kitchener and Shannon (98)	None	Average speed reduction in snow events 19.2 km/hr (based on comparison across events) Average speed reduction for snow floor (regression) is 3.5 km/hr	Average speed reduction for snow floor (regression) is 3.5 km/hr	Normal: sunny, clear, windless days Snow events are not defined
Enberg and Mannan (99)	None	Daylight speed reduction (ignoring volume effects) was 5-6 km/hr during snowfall, with 8-12 km/hr at night	No significant speed reduction found on slippery pavement conditions	Good winter conditions Slippery winter conditions Snowfall Rainy winter conditions

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