ASSESSMENT OF MONTANA ROAD WEATHER INFORMATION SYSTEM (RWIS)

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Final Report

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THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

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FEDERAL HIGHWAY ADMINISTRATION

January 2017

prepared by
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Assessment of Montana Road Weather Information System

Final Report

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Weather presents considerable challenges to highway agencies both in terms of safety and operations. State transportation agencies have developed road weather information systems (RWIS) to address such challenges. Road weather information has been used by highway agencies in many applications, the primary being for winter maintenance, but also for traveler information, and weather-related intelligent transportation system (ITS) applications. The Montana Department of Transportation (MDT) currently has 73 RWIS stations throughout the state that have been used as a major source of weather data for transportation applications. This project was undertaken to perform a comprehensive review and assessment of MDT's RWIS program to ensure the efficient use of weather data in various transportation applications and the optimum use of MDT resources.
Six major project tasks were completed for this project including a state of the art review, a state of the practice review, a Montana RWIS needs assessment, a weather data and software analysis, a benefit cost analysis, and the development of a site prioritization model. Methods and findings from each task are detailed in this report along with a set of recommendations including considerations for the future direction of MDT RWIS system.</td></tr>
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Table of Contents

List of Tables

List of Figures

Executive Summary

Weather presents considerable challenges to highway agencies both in terms of safety and operations. State transportation agencies have developed road weather information systems (RWIS) to address such challenges. Road weather information has been used by highway agencies in many applications, the primary being for winter maintenance, but also for traveler information, and weather-related intelligent transportation system (ITS) applications. The Montana Department of Transportation (MDT) currently has 73 RWIS stations throughout the state that have been used as a major source of weather data for transportation applications. This project was undertaken to perform a comprehensive review and assessment of MDT's RWIS program to ensure the efficient use of weather data in various transportation applications and the optimum use of MDT resources.

Six major project tasks were completed for this project including a state of the art review, a state of the practice review, a Montana RWIS needs assessment, a weather data and software analysis, a benefit cost analysis, and the development of a site prioritization model.

The state of the art review covered literature related to the history and use of RWIS, RWIS data adequacy and reliability knowledge in terms of different sensor and hardware technologies, site selection and geographic coverage practices, and preliminary benefit-cost findings from prior analyses. The review found that RWIS programs have expanded and evolved since their initial primary focus of winter maintenance support to include other uses like traveler information, operations activities, advanced ITS applications, and third-party weather service providers. RWIS technologies were found to be available from many vendors and manufacturers, and agencies are beginning to desire and require open architecture and flexible systems to allow for the use of technologies from more than a single provider. Traditionally environmental sensor stations (ESS) siting was a subjective process relying solely on personal judgement, and some agencies are starting to define systematic, objective ESS placement methods that attempt to quantify and optimize the knowledge held by agency personnel. Optimization models were found to be using data related to winter crash history, traffic volumes, and historical climate data. Overall the literature suggests RWIS programs produce many benefits that outweigh the costs; agency specific benefits like labor, materials, and equipment cost savings have benefit-cost ratios ranging from 1.1:1 up to 11:1, and when safety, operational, and other societal benefits are also considered the benefit-cost ratios increase and can exceed 40:1.

The state of the practice review focused on RWIS use, management, and planning and used a survey tool to solicit input from transportation agencies of all 50 States, Washington D.C., Puerto Rico, and the Canadian Provinces. Twenty-eight respondents completed the survey representing 24 states and 2 Canadian Provinces. Similar to the state of the art review, this survey found that RWIS data are being used for purposes including weather-responsive ITS and tracking weather-related performance metrics, but remain primarily focused on winter maintenance support. Operational data like traffic speeds, traffic volumes, and vehicle classifications, are not widely collected at most agencies' RWIS sites, but a couple of agencies do collect operational data at most/all RWIS locations. A few agencies have begun utilizing mobile RWIS as "non-trivial" portions of their program, and many others have begun to experiment with or use limited mobile RWIS equipment. Current funding and effort levels toward mobile RWIS remain low overall compared to traditional RWIS, but are anticipated to increase in the next five years. Many agencies collect mobile maintenance vehicle data (i.e. plow data, spreader data, Canbus data), but only a

few integrate that into their larger RWIS efforts. RWIS site placement is most commonly determined using agency personnel expertise, but some examples of other methods were cited including the use of geo-spatial analyses considering crash histories, climate histories, and traffic levels / road classifications as well as using public input, academic and consultant research, and thermal mapping analysis. Certain RWIS data types were thought to be almost unanimously essential including: pavement temperature, air temperature, pavement condition, wind speed and direction, and precipitation occurrence. Other data types that were thought to be at least helpful on average include: precipitation intensity/depth, humidity, precipitation type, visibility, still camera images, freeze temperature, chemical presence, friction, barometric pressure, and chemical concentration. Non-proprietary RWIS controllers and communications are now required for five of the responding agencies and desired in another eleven. Overall RWIS programs are still expanding with most agencies adding more sites for additional geographic coverage, many agencies enhancing existing locations with additional sensors, and some agencies adding mobile RWIS. In general, most agencies support the idea that more RWIS stations with fewer sensors (i.e. camera and pavement temperature only) would be better than fewer sites with their current configurations if made possible by cost savings using fewer sensors per site. Agency developed, custom software and Vaisala products are the most common software for displaying RWIS data for the responding agencies, but Delcan and Lufft were also cited. Typically RWIS software and hardware are operated and maintained either by agency personnel, Vaisala, or a combination of the two; other vendors (Lufft, Delcan and Narwhal Group) also perform these functions in a few responding agencies. Responses to open ended feedback found many respondents emphasizing the need for RWIS data display software on mobile devices, and improvements in using more mobile RWIS, non-invasive sensor technology, and non-proprietary systems.

A needs assessment for RWIS users was conducted using questionnaires and interviews with key MDT personnel to understand their weather information needs. Stakeholder groups included the primary users, winter maintenance personnel, and secondary users from traveler information and aeronautics. Maintenance personnel were found to need camera images, pavement conditions, air temperature, pavement temperature, wind speed and direction, precipitation type and occurrence, and visibility. All stakeholder groups generally favor the idea of having more sites with only a camera and pavement temperature sensor compared to fewer sites with more sensors per site. Maintenance personnel may also need wind sensors or visibility sensors at certain locations. It may be beneficial to update camera images and RWIS data every 15 minutes. The most problematic pieces of equipment from a maintenance perspective, the pan-tilt-zoom (PTZ) cameras, are also the most valuable. Cellular communications are the main source of RWIS data outages and those outages are out of MDT's control. There are certain sensor and camera technologies that may be desired including non-invasive sensors, more robust precipitation sensors, visibility sensors, live video, and cameras with the ability to produce images in the dark. The ability to display RWIS data for maintenance personnel on mobile devices is desired, but may be partially available currently via the traveler information mobile app. More RWIS sites are desired overall and especially near maintenance section boundaries. Mobile RWIS are not generally desired at the section supervisor / maintenance superintendent level, but more interest is shown at the maintenance chief level. Required RWIS software and server upgrades have recently resulted in some specific functionality losses, namely those related to condition and status alerts. RWIS data is widely used by the public via the traveler information systems from MDT. The public (via traveler information) may be the most common method for the agency to learn of unavailable or malfunctioning sensors and sites. Cameras are the most popular type of information for the public who would presumably prefer more camera-only sites compared to fewer fully-instrumented sites. RWIS is a secondary data source for the Aeronautics Division and general aviation uses in Montana, and camera images with horizon views may be the most valuable RWIS information for aviation.

A detailed weather data and software analysis was conducted and provides an overview of the current MDT RWIS system. It also identifies gaps in the current system compared to the needs of the agency, and identifies and analyzes potential hardware and software alternatives that may best meet the needs of the agency. MDT's RWIS program currently includes 73 ESS providing data for winter maintenance personnel and traveler information systems within MDT as well as sharing the data outside MDT to 511-provider Iteris, NOAA, and MSU/WTI for multistate traveler info/operations systems. The core sensor setup that exists at virtually all 73 ESS includes an air temperature and humidity sensor, wind speed and direction sensor, in-pavement sensor, subsurface temperature sensor, precipitation occurrence sensor, and a camera; select sites (6 or fewer) also have advanced precipitation sensors, visibility sensors, or infrared illuminators for nighttime camera images. MDT's internal RWIS software for data polling, processing and display is a legacy Vaisala system (SCAN Web 6.0) that no longer has the ability to provide weather condition or sensor/site status alarms, limited usability on mobile devices, and no forecasting functionality. Alternative sensors including various atmospheric combination sensors, infrared lights for cameras, visibility sensors, advanced precipitation sensors, and non-invasive sensors are available and may provide additional functionality or configuration options compared to the current core sensor setup. Many alternative RWIS software systems exist categorized by their functionality from basic observational only software to options for alerting, forecasting, mobile sensor integration and automated performance metric functionalities.

An extensive benefit-cost analysis was conducted to investigate outcomes related to using different software functionalities and geographic expansion alternatives. Agency specific benefits exceed costs for all three alternative software systems (alerting, forecasting and automated performance metrics) when considering the current ESS sites. The highest agency specific benefit-cost ratios were found to be possible with forecasting and automated performance metric functionalities. Total benefits, including societal benefits, exceed costs for all ESS expansion options (base, simple, non-invasive, and mobile) and all alternative software systems (alerting, forecasting and automated performance metrics). The highest total benefit-cost ratios were found to be possible with forecasting and automated performance metric functionalities. Most scenarios with the highest total benefit-cost ratios are also the most costly and may or may not be feasible with current MDT funding availability. Some of the most promising scenarios may require significant investments of hundreds of thousands of dollars above current RWIS funding amounts. One scenario, obtaining alerting functionality without expanding sites, is potentially both relatively low cost and highly beneficial, depending on the specific software product used.

An ESS site prioritization model was developed to increase the objectivity of a traditionally subjective practice for determining the best ESS placement given multiple potential sites. The model quantifies the overall merit of potential ESS sites based on historical weather conditions, traffic amounts, crash history, existing geographic coverage and opportunistic factors related to the availability of power and communications. The model is customizable and allows MDT to place selected weights on certain aspects according to their agency priorities.

Overall the MDT RWIS program provides many benefits to MDT users and ultimately the traveling public. A number of minor practical recommendations and larger program future direction possibilities exist, stemming from the tasks considered as a whole. MDT should consider requiring new RWIS sensor, hardware, and software options be as flexible as possible through the use of non-proprietary communications and compatibilities, allowing for easy integration of different equipment that may be superior or more economical regardless of the provider. RWIS data and camera images should be updated every 15 minutes or less for all sites as some RWIS data users and literature suggest that 15 minutes can make a considerable difference in terms of winter maintenance treatments, especially at the start of a storm. Aviation users would benefit by including a horizon view at all ESS with PTZ cameras, especially considering adding this view at ESS with PTZ cameras will not detract from primary road monitoring images. Some winter maintenance personnel in remote areas currently have little or no RWIS coverage so it may be beneficial to make those personnel aware of resources like http://mesowest.utah.edu/ that have additional weather observations from non-RWIS sites around the state. MDT could benefit from a less subjective site selection process that is data driven by utilizing the ESS prioritization model with agency selected weights that reflect their knowledge and preferences to plan future RWIS installations. Lastly a number of future directions show promise in reducing agency costs and increasing safety and mobility for travelers. These future directions require obtaining new software products and services and considering different geographic expansions all at varying initial and ongoing levels of investment and some with non-trivial changes to winter maintenance practices.

1) INTRODUCTION

Weather presents considerable challenges to highway agencies both in terms of safety and operations. From a safety standpoint, snow, ice and other forms of precipitation may reduce pavement friction, increasing the potential for crashes when vehicles are traveling too fast for the conditions. From an operations standpoint, heavy snow storms may affect the connectivity of the highway network due to closures that need to be cleared in an efficient and timely fashion. Further, travelers should be informed about unusual pavement conditions and road closures on time to minimize the effect of adverse weather on the safety and mobility of the traveling public. For the aforementioned reasons, road weather information has become increasingly important for highway agencies particularly in states (and regions) that experience harsh winter weather conditions. Road weather information has been used by highway agencies in many applications such as winter maintenance, traveler information, and other weather-related intelligent transportation system (ITS) applications. The adequacy, reliability, and geographic coverage are critical aspects of weather data to be used effectively in those applications by transportation managers.

Montana Department of Transportation (MDT) currently has 73 Road Weather Information System (RWIS) stations throughout the state that have been used as a major source of weather data for transportation applications. All these RWIS stations are fixed and other entities (such as the National Weather Service) currently rely on these stations for information. The number and location of these environmental sensor stations were largely determined over time by the pressing needs of the maintenance and snow removal operations, without much consideration to other applications that are in need of accurate and timely road weather data. Therefore, this project was undertaken to perform a comprehensive review and assessment of the state road weather data collection program to ensure: 1) the efficient use of weather data in various transportation applications and 2) the optimum use of MDT resources.

Six major project tasks were completed for this project. This final report consists of eight chapters, one chapter for each of the six projects tasks, one chapter for introduction and another chapter for conclusions and recommendations. The chapters are:

1. Introduction (this chapter),
2. State of the Art Review,
3. State of the Practice Review,
4. Needs Assessment,
5. Weather Data and Software Analysis,
6. Benefit Cost Analysis,
7. Site Prioritization Model, and
8. Conclusions and Recommendations.

2) STATE OF THE ART REVIEW

RWIS are networks of weather sensors used by transportation agencies to monitor weather occurring on the roads they maintain. The earliest instances of RWIS deployment are documented in the 1970s and those early deployments were mainly focused on providing information to assist with winter road maintenance (PB & Iteris, 2013a). RWIS programs have expanded from their initial focus to include a broader set of stakeholders and data users as well as new and more diverse technologies. RWIS programs now regularly serve not only department of transportation (DOT) maintenance personnel, but traveler information personnel, operations personnel, advanced ITS applications, the travelling public, and third-party service providers.

Today most environmental sensor stations (ESS) for RWIS typically include various atmospheric sensors, some form of pavement sensor, and camera imaging. Additional sensors are also being added to some ESS locations to measure traffic volumes, traffic speeds, and vehicle classifications and weights (Hawkins & Albrecht, 2014). Mobile sensors are also being utilized by many agencies to measure road and atmospheric conditions in real-time attached to maintenance vehicles. Each of these sensor combinations allow for different end user benefits as shown in Figure 1.

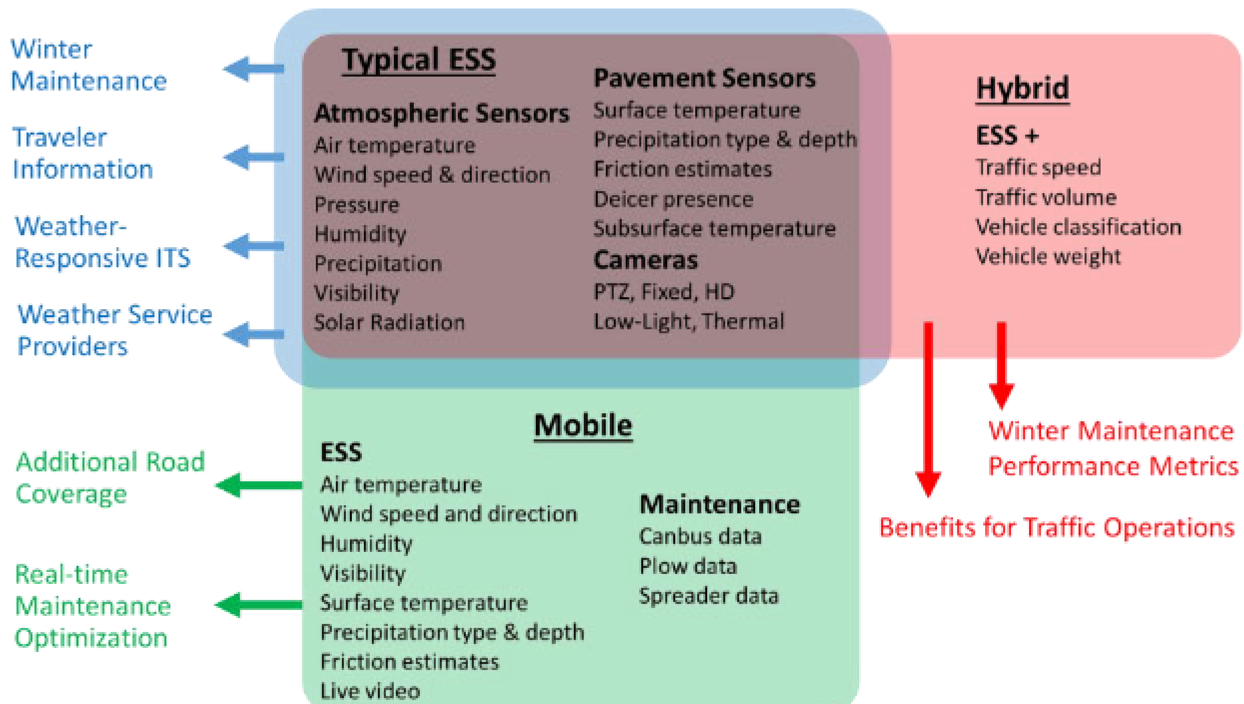


Figure 1: RWIS Components and Uses

RWIS networks also allow for maintenance decision support systems (MDSS) which assist winter maintenance personnel in performing winter ice and snow clearing operations. Pavement condition forecasting efforts have also been advanced to assist practitioners by providing likely pavement surface conditions given the observed and forecast weather patterns, maintenance activities, and traffic (Feng & Fu, 2014).

What started as an efficient means for DOT maintenance personnel to monitor weather remotely and react accordingly has grown to be valued by other interests and as a result the technologies employed by traditional RWIS have been added to and adjusted. This chapter reviews all literature pertaining to RWIS, focusing on data adequacy and reliability, picture and video technologies, geographic coverage, and benefit-cost analyses both for the primary stakeholder, DOT maintenance staff, as well as the additional end users.

2.1. Data Adequacy and Reliability

Data adequacy and reliability are dependent upon the intended uses of the sensor measurements. For instance, adequate data for traditional winter maintenance uses may be different than adequate data for releasing to the travelling public or monitoring the traffic impacts of winter storms. Similarly the different uses of RWIS data can require different levels of reliability; e.g. a weather-responsive variable speed limit sign may require higher reliability than general traveler information. In general, high reliability has been considered paramount to the success of an RWIS program, and high reliability is often dependent on system maintenance, training and dependable communications (Abdi et al., 2012, Ballard et al., 2002, Battelle, 2006 and Boon & Cluett, 2002). General accuracy and reliability concerns were uncovered occasionally during this review, however, specific figures relating to accuracy and reliability are not typically found in the unbiased literature. The following subsections detail the types of data acquired from each of the various types of sensors and any information uncovered regarding their typical accuracy and/or reliability.

The reader should be mindful that sensor capabilities and technologies are often only available from manufacturer sources, so the following sections do identify sensor producers and general producer information, but use no quality or reliability conclusions based on manufacturer information. Any and all documented statements of quality or reliability stem only from previously published unbiased evaluations and studies.

Many manufacturers and vendors produce atmospheric and pavement weather sensors capable for use in RWIS applications. A handful of companies seem to be aimed at providing comprehensive RWIS sensor packages, while many other companies are focused on providing one or a few technologies that may then be part of larger RWIS packages. Companies that could be identified as providing comprehensive packages of RWIS sensors (including both atmospheric and pavement sensors) in the US are shown in Table 1.

Table 1: Comprehensive RWIS Providers in the US

Producer	Nearest Location	Atmospheric Sensors							Pavement Sensors	
		Air Temp.	Humidity	Pressure	Solar Rad.	Visibility	Wind	Precip.	In-Pave.	Non-Inv.
Aanderaa Data Instruments	Massachusetts	X	X	X	X	X	X	X	X	
All Weather Inc.	California	X	X	X	X	X	X	X	X	
Boschung	Colorado	X	X	X	X	X	X	X	X	
Campbell Scientific	Utah	X	X	X	X	X	X	X	X	
Geonica via Advanced Monitoring Methods	Colorado	X	X	X	X	X	X	X	X	X
High Sierra Electronics	Utah	X	X	X	X	X	X	X	X	X
Lufft	California	X	X	X	X	X	X	X	X	X
Vaisala	Colorado	X	X	X	X	X	X	X	X	X

(list compiled with assistance from databases maintained by The Association of Hydro-Meteorological Equipment Industry (HMEI) website at hmei.org and meteo-technology.com)

While these RWIS providers typically manufacture some of their own sensors, it is not uncommon to see re-branded sensors that may come from other sources. Table 2 shows a sample of identifiable weather sensor providers (both US and International) and the technologies they offer either themselves or indirectly through the comprehensive RWIS providers.

Table 2: Weather Sensor Providers

Producer	Sensors
Belfort Instrument (belfortinstrument.com)	Full suite of atmospheric sensors
Biral (biral.com)	Full suite of atmospheric sensors
Cimel (camel.fr)	Full suite of atmospheric sensors
Climatronics (climatronics.com)	Full suite of atmospheric sensors
Coastal Env. Syst.s (coastalenvironmental.com)	Full suite of atmospheric sensors
Envirotech Sensors (envirotechsensors.com)	Visibility sensors
Eppley Laboratory (eppleylab.com)	Solar radiation sensors
Kipp and Zonen (kippzonen.com)	Solar radiation sensors
Logotronic (logotronic.at)	Full suite of atmospheric sensors
Met One Instruments (metone.com)	Full suite of atmospheric sensors
NovaLynx (novalynx.com)	Full suite of atmospheric sensors
Optical Scientific (opticalscientific.com)	Full suite of atmospheric sensors
Paroscientific (paroscientific.com)	Air temperature, humidity and pressure sensors
Pulsonic (pulsonic.net)	Full suite of atmospheric sensors
RM Young (youngusa.com)	Full suite of atmospheric sensors
Rotronic (rotronic-usa.com)	Air temperature, humidity and pressure sensors
Sensice (sensice.com)	Non-invasive road surface sensors
Setra (setra.com)	Air temperature, humidity and pressure sensors
Sterela (sterela.fr)	Full atmospheric (unknown pavement sensors)
Sutron (sutron.com)	Full suite of atmospheric sensors
Texas Electronics (texaselectronics.com)	Full suite of atmospheric sensors
Yankee Env. Systems (yesinc.com)	Full suite of atmospheric sensors

(list compiled with assistance from databases maintained by The Association of Hydro-Meteorological Equipment Industry (HMEI) website at hmei.org and meteo-technology.com)

2.1.1. Atmospheric and Pavement Sensors

Most atmospheric and pavement sensor types have been used for some time now. Many of the attributes measured by atmospheric and pavement sensors (air temperature, pavement temperature, wind speed & direction, precipitation type, and humidity) have been found to be among the most accurate and reliable of all road weather characteristics examined by a national survey of surface transportation personnel (Hart et al., 2009).

Air Temperature, Humidity, and Barometric Pressure

Air temperature, humidity and barometric pressure sensors can be individual sensors or be part of clustered sensors that can measure many attributes. Most installations utilize air temperature and humidity together to calculate a dew point temperature. Figure 2 shows some typical temperature, humidity, and pressure sensors with an air temperature only sensor (left), air temperature and humidity sensor (center), and an air temperature, humidity, pressure, solar radiation, and wind speed and direction sensor cluster (right).

Figure 2: Air Temperature, Humidity and Barometric Pressure Sensors

No relevant reliability concerns were identified regarding the use of these air temperature, humidity, and barometric pressure sensors for RWIS applications.

Solar Radiation

Solar radiation sensors, also known as pyranometers, can be part of clustered sensors as shown in Figure 2 (far right) or be individual sensors like those shown in Figure 3.

Figure 3: Solar Radiation Sensors

No relevant reliability issues were identified regarding the use of these solar radiation sensors for RWIS applications.

Visibility

Visibility sensors are available in a few different designs and can be standalone sensors, or be integrated into weather sensors that measure both visibility and precipitation data. Figure 4 shows different visibility sensors with a standalone sensor (left) and visibility with precipitation sensors (center and right).

Figure 4: Visibility Sensors

Documented issues regarding these sensors include:

- Visibility and precipitation sensors that utilize optical sensing methods are susceptible to lens cleaning requirements as winter road slush and debris can cause problems if the sensing lens becomes obstructed (PB & Iteris, 2013b).
- In one documented instance backscatter visibility sensor technology was found to be unreliable and replaced with forward-scatter visibility sensors (Murphy et al., 2012).

Wind

Wind sensors that measure wind speed and direction are typically either mechanical (anemometer and vane) or ultrasonic sensors (with no moving parts). Ultrasonic wind sensors can be standalone or part of clustered sensors like that shown in Figure 2 (far right). Figure 5 shows some of the standalone wind speed and direction sensor types available.

Figure 5: Wind Sensors

Mechanical wind sensors were the only option for some time and performed adequately, but remain susceptible to icing problems and require regular maintenance especially on bearings. The low maintenance ultrasonic wind sensors are becoming more popular, evidenced by agencies like Michigan DOT who are exclusively using ultrasonic wind sensors on all new RWIS deployments (Hoch et al., 2006 and PB & Iteris, 2013b).

Precipitation

Atmospheric precipitation sensors also come in a variety of forms with some being mechanical (tipping bucket type) to measure precipitation rate, and others using optical, infrared, or radar technologies to determine precipitation type and intensity. Figure 6 shows the types of atmospheric precipitation sensors available from RWIS vendors.

Figure 6: Precipitation Sensors

Documented issues regarding these sensors include:

- Again, visibility and precipitation sensors that utilize optical sensing methods are susceptible to lens cleaning requirements as winter road slush and debris can cause problems if the sensing lens becomes obstructed (PB & Iteris, 2013b).
- High winds can also cause optical type precipitation sensors to overestimate precipitation rates (PB & Iteris, 2013b).

In-Pavement

Sensors embedded into the road surface are used to determine pavement temperature, subsurface temperature, and road surface conditions such as deicer presence, freeze temperature, precipitation presence and depth, and friction estimates. These sensors can measure one or a number of these attributes depending on the model. Figure 7 shows four in-pavement sensors from different RWIS vendors.

Figure 7: In-Pavement Sensors

Documented issues regarding these sensors include:

- Past work has documented pavement temperature sensor reliability and accuracy issues (Ballard et al., 2002 and STWRC, 2009). Note: these issues are somewhat dated, so the causes for the problems may since have been addressed by the manufacturer or agency personnel.
- In one study, the “chemical presence and concentration detectors [were] notoriously unreliable” (Boon & Cluett, 2002). Concern was also voiced about these chemical concentration sensors by Zwahlen et al. (2003). Again note: these concerns are dated now, and may or may not have been improved. They could also be related to the fact that certain sensors are calibrated for specific deicing chemicals only (Mitchell et al., 2006).

<u>Non-Invasive</u>

Non-invasive pavement sensors are installed above the roadway either on a gantry or pole near the roadside. This more recent sensor technology has been evaluated and been found to be generally reliable for many transportation applications (Ewan et al., 2013). Non-invasive pavement sensors utilize infrared technology to determine road temperature and surface conditions like precipitation presence, type and depth, and a road surface friction estimate.

Figure 8: Non-Invasive Pavement Sensors

Documented issues regarding these sensors include:

- These non-invasive road weather sensors have a maximum measuring distance to the road surface. This maximum distance is often less than what many existing ESS tower installation would allow, and as such may require an additional mounting platform to be used (PB & Iteris, 2013b).

- The accuracy of the measurement of precipitation depth can be dependent on sensor installation angle for some non-invasive pavement sensors, therefore special considerations may be required for installation mounting geometries (Al-Kaisy et. al., 2012).

2.1.2. Camera Technologies

Camera technologies and remote monitoring have evolved since the emergence of RWIS programs and it is becoming increasingly common to have cameras at most ESS locations. As of 2007 there were over 10,000 cameras continuously monitoring major roadways in the US (Hallowell et al., 2007). Image processing is now possible on site and this coupled with network communications has made additional camera uses besides just live video monitoring a possibility. While not necessary for most RWIS applications, new camera capabilities like vehicle counting, vehicle classification, license plate recognition, and automated incident detection are possible (Axis, 2014). High definition, thermal imaging, and low-light technologies are recent advances that can improve the overall capabilities of transportation infrastructure monitoring (Mobotix, 2015). Tradeoffs between camera functionality, image quality and data transfer can dictate what cameras are used for at ESS locations. Cameras can be fixed and constantly aimed at one viewing area or be pan-tilt-zoom (PTZ) type that allow for remote control to change the viewing area and zoom level. A sample of some comprehensive camera providers that serve the transportation sector include:

- Adventura Technologies (aventuracctv.com),
- Arecont Vision (arecontvision.com),
- Axis Communications (axis.com),
- CohuHD (cohuhd.com),
- Infinova (infinova.com),
- Mobotix (mobotix.com),
- Pelco / Schneider Electric (pelco.com),
- Siqura (siqura.com),
- Vicon - including recently acquired IQinVision (vicon-security.com), and
- Wireless Technology Inc. (gotowti.com)

Regardless of the type of cameras used, the communication technology can also influence the quality and capabilities of the imaging. Internet Protocol (IP) network cameras are becoming more common and may offer some advantages over analog cameras especially in remote locations where agencies may desire still images to be transferred at regular time intervals (Duplack, 2015). As a technology, IP network cameras may allow for certain capabilities not available with analog cameras including potentially better image quality, single cable to transfer data / power / PTZ controls, and on-site video image processing (Axis, 2009).

Documented issues regarding cameras at ESS locations include:

- Low-light situations can render some camera images useless, therefore it is advisable to use cameras that include technologies that allow for functionality in low light conditions (PB & Iteris, 2013a).
- Mounting structures effected by wind or vibrations can cause poor image quality (McGowen, 2008).

2.1.3. Mobile Sensors

Mobile sensors are a more recent technology to be integrated into RWIS. Currently mobile road weather sensors are capable of measuring road temperature, and surface conditions such as precipitation type and depth, as well as surface friction estimates, and ambient air temperature and humidity. Mobile road weather sensors have unique communications challenges, but can allow for valuable benefits like real-time winter maintenance optimization, additional RWIS geographic coverage, and operational data related to winter storm clearance and safety improvements (Lapointe, 2011). Figure 9 shows the mobile road weather sensors available from the RWIS providers.

Figure 9: Mobile Sensors

One issue regarding mobile sensors was stated: “mobile sensor systems have performed well when attached to light-duty vehicles, but struggle in the harsh environment that surrounds snowplows during plowing operations” (PB & Iteris, 2013b).

2.1.4. General Issues Identified

Overall, most of the reliability concerns with RWIS data stem from earlier evaluations and instances with DOT personnel that may not have had adequate experience with RWIS equipment. This may also have been exacerbated by poor maintenance programs, training practices and/or unfamiliar sensor technologies. Today RWIS data seems to be more reliable and more trusted by agency personnel than before, but general reliability concerns continue to be sparsely documented.

Documented issues regarding RWIS overall (with no specific sensor type identified) include:

- A recent survey of 37 RWIS personnel in New York found that about 30% of respondents were dissatisfied with the reliability of RWIS equipment and data transmission (Chien et al., 2014).
- Certain RWIS equipment power supplies have also been documented to have issues in very cold temperatures (ITS Int., 2013).

- In general, maintenance and knowledgeable technicians go a long way toward ensuring reliable sensor outputs, and as such many DOTs are choosing to solve data reliability issues by contracting to a service vendor with performance contracts that ensure certain levels of accuracy and reliability without having to train their own personnel (PB & Iteris, 2013a).
- Proprietary system architecture designs can be limiting and therefore open ESS system architecture designs are now desired by many agencies to allow for flexibility and inclusion of sensors and technologies from multiple producers (Ballard et al., 2002, Battelle, 2006, PB & Iteris, 2013a, and STWRC, 2009,).

2.2. Geographic Coverage

RWIS programs have continued to expand geographically in many states over the past decade. States that face significant winter weather challenges like Montana typically have extensive networks of ESS. Table 3 shows the number of ESS and approximate coverage characteristics for states that experience significant winter weather.

Table 3: ESS by State

State	Number of ESS	Land Area (sq. mi)	Select Road Miles	Approx. Road Miles Covered per ESS	Approx. Land Area Coverage Radius (miles) per ESS
MT	73	145,546	4,180	57	25
CO	150	103,642	4,462	30	15
ID	125	82,643	2,572	21	15
IA	96	55,857	5,020	52	14
MI	66	56,539	5,257	80	17
MN	95	79,627	5,217	55	16
NY	45	47,126	5,665	126	18
ND	26	69,001	3,645	140	29
OH	172	40,861	5,634	33	9
OR	71	95,988	4,077	57	21
SD	46	75,811	3,679	80	23
UT	83	82,170	2,740	33	18
WA	120	66,456	3,559	30	13
WI	59	54,158	5,523	94	17
WY	82	97,093	3,055	37	19

Select Road Miles: (FHWA, 2013a) including Interstates, freeways, and principal arterials. Land Area: (US Census Bureau, 2015). Number of ESS: (FHWA, 2013b), (Hawkins & Albrecht, 2014), (PB & Iteris, 2013a).

ESS alone can provide valuable information for local uses, but once certain levels of geographic coverage are reached additional area wide forecast benefits can be realized. If located properly, ESS can serve both local and larger regional needs (Manfredi et al., 2008). The quality of data and level of benefits realized by having a large network of ESS is dependent on the geographic placement of the stations. Perhaps the most common and traditional method for geographic ESS placement has been to rely on local expertise including knowledge from maintenance personnel and meteorologists (Ballard et al., 2002, Kwon and Fu, 2013 and Manfedi et al., 2008). In addition to local expertise, logistical concerns have also dictated ESS placement practices especially in remote locations: logistical concerns like the presence of power and communications and the proximity to maintenance shops such that routine maintenance can be performed in a single day (Hoch et al., 2006, McGowen, 2008, and Zwahlen et al., 2003).

2.2.1. General Guidance

The most recent FHWA ESS Siting Guidelines (Manfedi et al., 2008) provide details concerning local siting, but little specific guidance for macro-scale geographic ESS placement beyond relying on DOT personnel and meteorologists. In general, the authors state that the placement of regional ESS should be on relatively flat, open terrain on the upwind side of the road.

Zwahlen et al. (2003) have identified many additional factors to consider when determining the placement of ESS including: climatic history, road class, traffic volumes, locations with high grades, crash history, and common storm pattern movement directions. While these factors are listed, a method for using them for geographic placement is not described in the report.

Researchers in North Dakota (STWRC, 2009) determined that a 30 mile radius coverage area should not be exceeded in order to discern finer scale weather patterns given North Dakota's land-use and terrain. This is in-line with the FHWA guidelines recommendation of up to 20 to 30 miles for regional ESS (Manfedi et al., 2008). Using this general guideline and the existing ESS network, the researchers provided 18 additional recommended ESS locations to ensure more comprehensive coverage. Figure 10 shows the existing (brown) and proposed supplemental (blue) ESS sites and their 15 and 30-mile coverage radii.

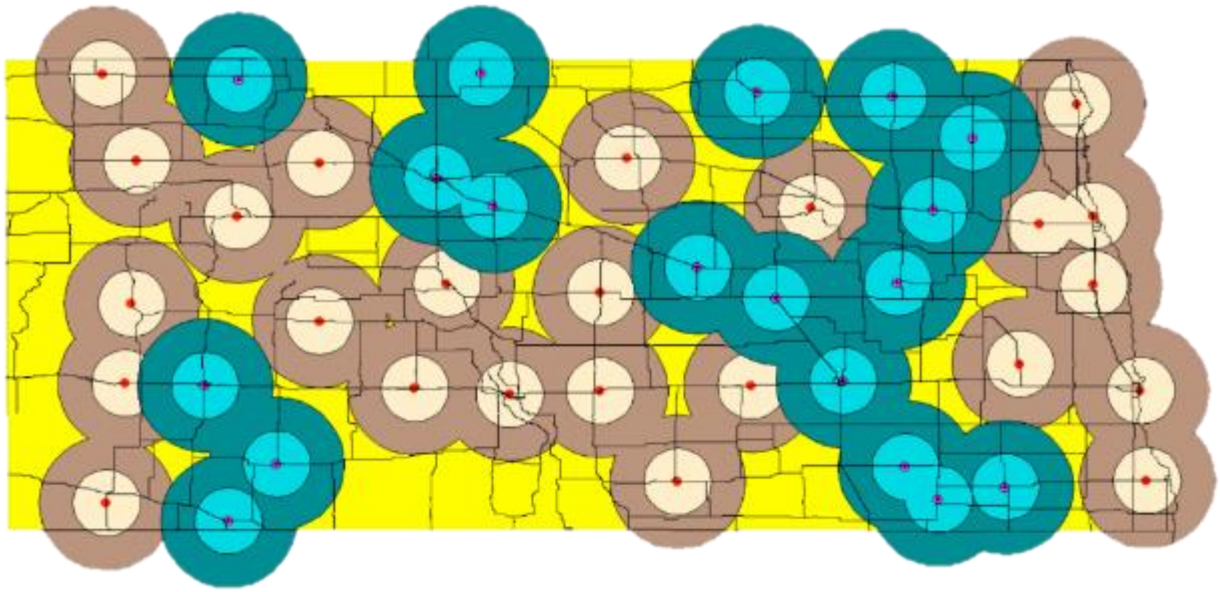


Figure 10: ESS Supplement Plans for North Dakota (STWRC, 2009)

2.2.2. Systematic Approaches

Efforts in recent years have attempted to develop siting procedures that involve somewhat more objective and analytical means to determine geographic ESS placement. Analyzing the potential placement of 10 ESS in the Austin Texas region, Jin et al. (2014) developed a placement optimization model that was driven primarily by weather-related crash history. The authors developed a safety concern index based on past weather related crash occurrence then spatially optimized the placement of the 10 ESS to obtain the greatest risk coverage assuming a 10 mile area coverage radius per ESS. Figure 11 shows the optimized ESS placement plans for different crash analysis years.

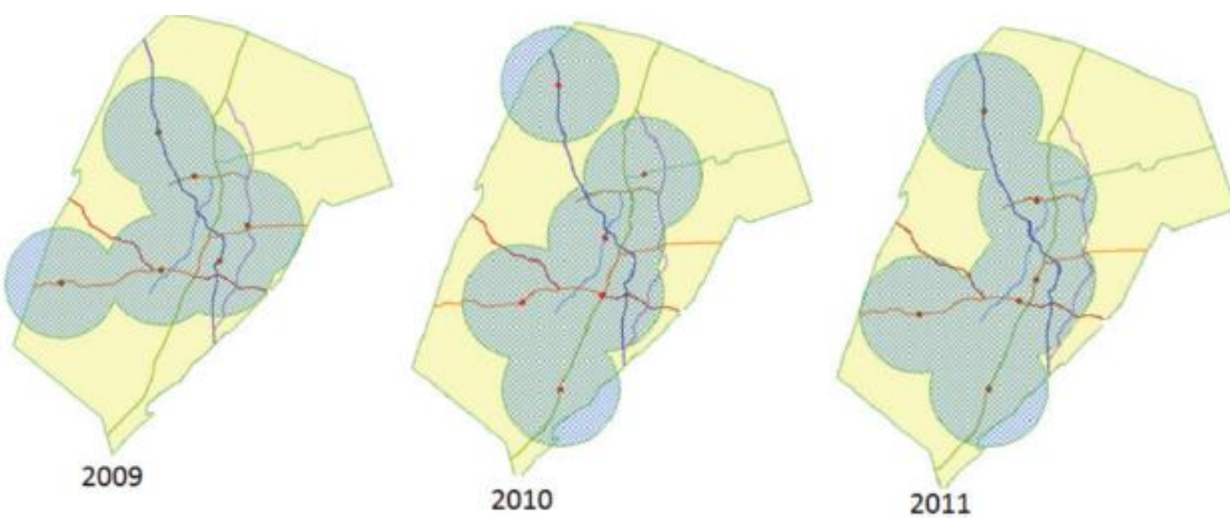


Figure 11: ESS Placement Optimization Models for Austin Area (Jin, et. al., 2014)

During the initial design (Pinet & Lo, 2003) of Alberta's RWIS network and a later expansion (Pinet & Bielkiewicz, 2009) the authors described the geographic siting procedures considering many factors. Topography, hydrology, meteorological zones, winter crash statistics, traffic volumes and expertise from local meteorologist helped define influence areas for each ESS as well as the overall placement of the RWIS network. The initial RWIS locations were limited to the National Highway System and the expansion designs branched out from the initial placements. Figure 12 shows the initial placement design (left) with the approximate coverage areas and the expansion design (right).

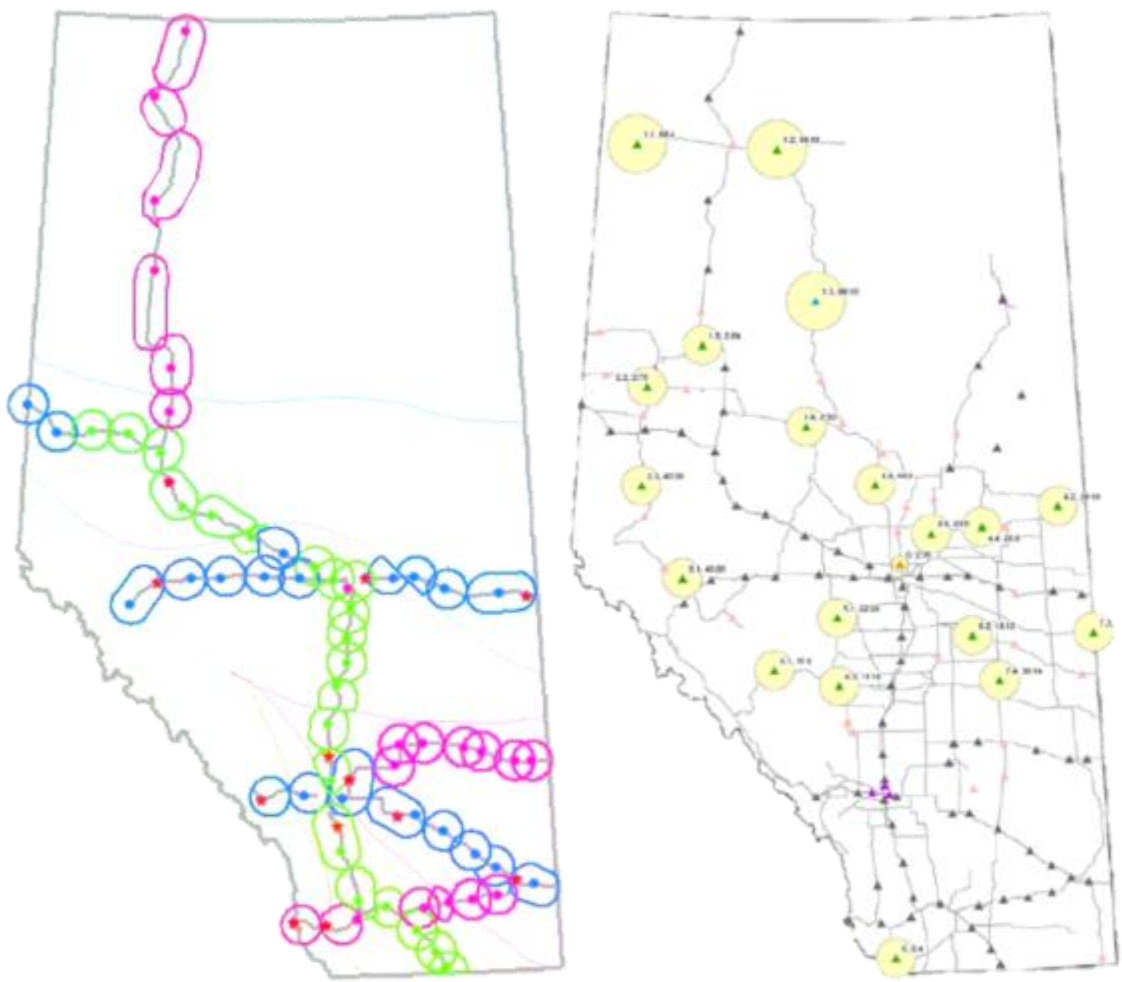


Figure 12: ESS Placement Plans for Alberta (Pinet & Bielkiewicz, 2009)

Kwon and Fu (2013) developed geographic ESS placement methods based on multiple factors including surface temperature variability, mean surface temperatures, precipitation amounts, traffic volumes, crash rates, and highway classification. The authors also investigated case studies of their methods using different combinations of the placement factors for Ontario, Canada. The study area was first broken into equal sized cells for analysis, next only cells containing the relevant road network were considered as candidates for ESS placement, and then the analyses using the factors above were performed resulting in the candidate locations. Figure 13 shows one of the placement models with the highest 140 ranked candidate locations highlighted and grid shading according to the prioritization from a combination of all factors.

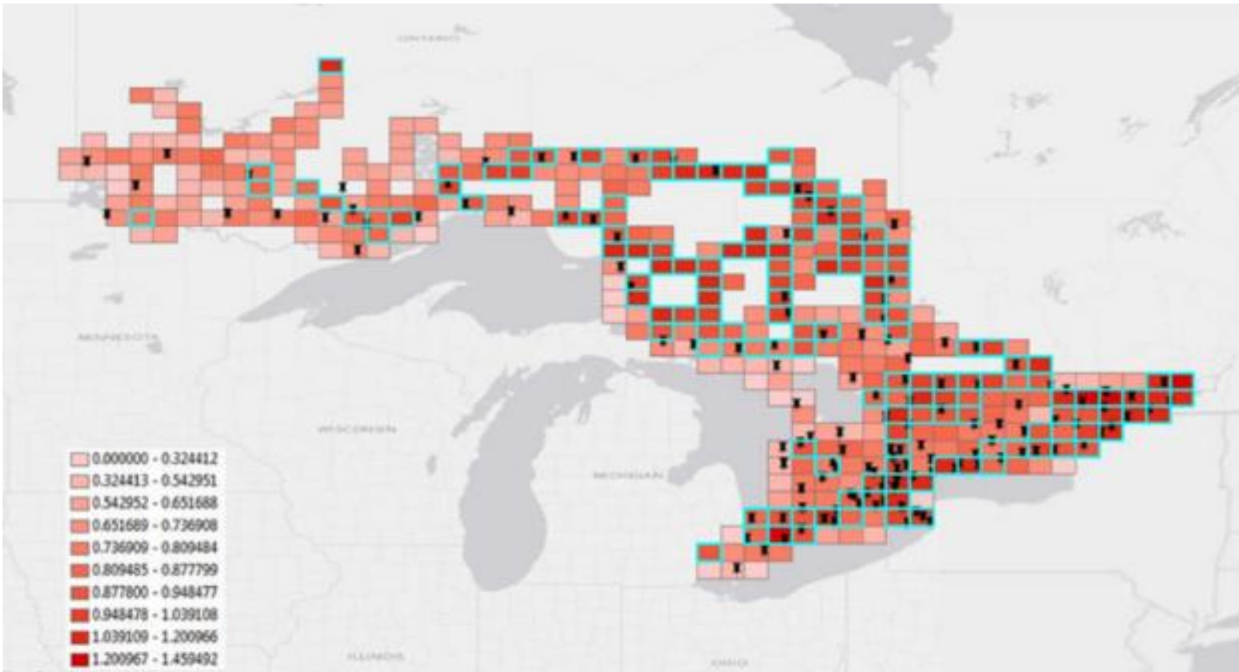


Figure 13: ESS Placement Model for Ontario (Kwon and Fu, 2013)

Yang and Regan (2014) developed a methodology to prioritize the placement of ESS for RWIS in South Korea. Their methods for prioritizing placement of ESS includes factors related to snow vulnerability analysis, winter crash statistics, traffic volumes, and the presence of nearby cameras. The initial areas prone to snow were identified by personnel in regional offices and additional snow vulnerability analysis was performed on these areas. Next, these areas were reduced to eliminate places that already had ESS or nearby automatic weather stations (AWS) that were placed appropriately to provide ESS type road weather information. Finally, the remaining areas were prioritized by considering winter crash history, traffic volumes, and whether or not a camera was installed nearby.

2.3. Benefit – Cost Relationships

Weather causes significant challenges for transportation agencies. The economic impact of weather related crashes tops $42 billion each year and transportation agencies spend another $2 billion on snow and ice removal (FHWA-RITA, 2010). RWIS programs do offer many benefits to try to mitigate these costs. A considerable number of benefit cost analyses for RWIS have been reported in the published literature. These analyses often consider different components when determining a benefit to cost ratio. Recently FHWA published a Road Weather Benefit Cost Analysis Compendium which reviews some past efforts and provides tools to help practitioners perform future benefit-cost analyses (Lawrence et al., 2014). Different analyses consider different costs and different benefits be they agency specific benefits or societal benefits.

Typical RWIS costs considered can include (Boselly, 2002, Fay et al., 2010, and Lawrence et al., 2014):

- Design / Engineering,
- Land acquisition,
- Construction / Installation,
- Sensors / Equipment,
- Power,
- Communications,
- Training,
- Maintenance, and
- 3rd Party Services

Typical RWIS benefits considered can include (Boselly, 2002, Fay et al., 2010, and Lawrence et al., 2014):

Agency Specific

- Materials: less winter maintenance materials used;
- Labor: less personnel hours needed; and
- Equipment: reduced equipment wear

Societal

- Safety: fewer and/or less severe crashes;
- Operations: improved travel times, reduced delay, improved level of service;
- Travel Information: improved and timely information for travelers;
- Infrastructure: less wear on roads, bridges, guardrail; and
- Environmental: less fuel consumption, less impact to roadside environment

Many of the benefit-cost studies documented are prepared assuming some aspects of the program costs and benefits to develop anticipated benefit-to-cost (B:C) ratios prior to deployment. Some analyses attempt to capture actual post-deployment costs and benefits, but assigning clear cause and affect relationships from RWIS deployments is not always definitively possible. Table 4 shows the documented studies that published benefit-cost relationships as well as the factors considered and whether the analysis was anticipated (pre-deployment) or post-deployment.

Table 4: Benefit – Cost Studies

Location (Reference)	Costs	Benefits: Agency Specific	Benefits: Societal	B:C Ratio
Alberta, Canada (AIT, 2006)	Undefined	Materials Labor	Safety	5.4 : 1 (anticipated)
Washington (Boon & Cluett, 2002)	Undefined	Materials Labor		5 : 1 (anticipated)
Colorado (Boselly, 2002)	Equipment 3rd Party Services	Materials Labor Equipment		1.1 : 1
Wisconsin (CRC, 2002)	Undefined	Materials Labor	Safety	5 : 1 to 15 : 1
New York (Chien et al., 2014)	Design Installation Equipment Power Communications Maintenance	Materials Labor Equipment	Safety Operations Infrastructure Environmental	10 : 1 to 15 : 1 (anticipated)
Idaho (Koeberlein et al., 2015)	Undefined		Safety	22 : 1
Utah (Strong and Shi, 2008)	Undefined	Materials Labor		11:1
Iowa (Veneziano et al., 2014)	Installation Equipment Power Communications Training Maintenance 3rd Party Services	Materials Labor Equipment		3.8 : 1
Iowa (Veneziano et al., 2014)	Installation Equipment Power Communications Training Maintenance 3rd Party Services	Materials Labor Equipment	Safety	45 : 1
Iowa (Ye et al., 2009a)	Maintenance 3rd Party Services	Materials Labor Equipment		1.8 : 1
Nevada (Ye et al., 2009b)	Maintenance 3rd Party Services	Materials Labor Equipment		3.2 : 1
Michigan (Krechmer et al., 2008)	Installation Equipment Maintenance	Materials Labor	Safety Operations	2.8 : 1 to 7 : 1

From the documented RWIS benefit-cost studies, it follows that agency specific benefit cost ratios range from 1.1:1 to 11:1 and overall benefit cost ratios (including societal benefits) range from approximately 3:1 to 45:1 depending on the factors considered. Regardless of the methods used, there seems to be a consensus that, in general, RWIS benefits outweigh the costs and particularly so when societal costs are considered besides agency costs.

2.4. Summary

RWIS programs have evolved from their original intent, but remain focused primarily on winter maintenance and safety benefits. New technologies and capabilities have also contributed to RWIS serving many end users for different purposes including traditional winter maintenance, traveler information, operations activities, advanced ITS applications, and third-party weather service providers.

Many sensor technologies exist that are aimed at providing road weather observations. Most of these technologies have been used successfully for some time now, but proper maintenance and reliable communications are a must to ensure quality and timely data. Certain considerations for specific sensor technologies documented in past works can guide new acquisitions and maintenance practices. Newer mobile sensor technologies hold promise for future applications. Where there once was only one major RWIS vendor, there are now multiple providers which allows for multiple technology sources. Open architecture type systems are more flexible and are often desired now more than ever by transportation agencies.

States faced with winter challenges typically have large networks of ESS to ensure considerable coverage of the roads they are tasked with maintaining. In the past, only general guidance on geographic ESS placement was available and it consisted mostly of relying on local expertise from agency personnel and meteorologists. More recent efforts have begun to define systematic, objective ESS placement methods that attempt to quantify and optimize the knowledge traditionally held by agency personnel. Optimization models using data related to winter crash history, traffic volumes, and historical climate data are now being proposed.

Overall, RWIS programs have produced many benefits that typically outweigh the cost considerably. Transportation agency specific benefits like labor, materials, and equipment cost savings have benefit-to-cost ratios ranging from 1.1:1 up to 11:1. When safety, operational, and other societal benefits are also considered the benefit-to-cost ratio increases and can exceed 40:1.

3) STATE OF THE PRACTICE REVIEW

This chapter details the findings from a survey which was conducted to establish the state of practice pertaining to RWIS use, management, data, and planning. Certain aspects of the state of practice of RWIS have been previously documented in other projects including work performed by Chien et. al. (2014), Hawkins & Albrecht (2014), PB & Iteris (2013a), Shi et. al. (2007), and Mitchell et. al. (2006). The PB & Iteris (2013a) work is most relevant to this project and contains much about the state of practice of RWIS related to current RWIS configurations and data. Overall, 20 transportation agencies were interviewed by PB & Iteris, with the report being publish in 2013. This recent work with many respondents establishes the configurations of RWIS around the country including which provider's and technologies are used throughout the responding agencies.

The survey for this project focuses on RWIS use, management, and planning and does not reproduce the RWIS configuration type questions and information that other projects have recently completed. The survey used for this state of practice review was created and administered using Qualtrics survey software. The survey was sent to transportation agencies of all 50 States, Washington D.C., Puerto Rico, and the Canadian Provinces. Twenty-eight (28) respondents completed the survey representing 24 states (2 states with multiple responses), and 2 Canadian Provinces. Figure 14 shows the U.S. state transportation agencies that completed the survey marked in red (two responses were received from both California and Wyoming). Personnel from the Canadian Provinces of British Columbia and Quebec also completed the survey.

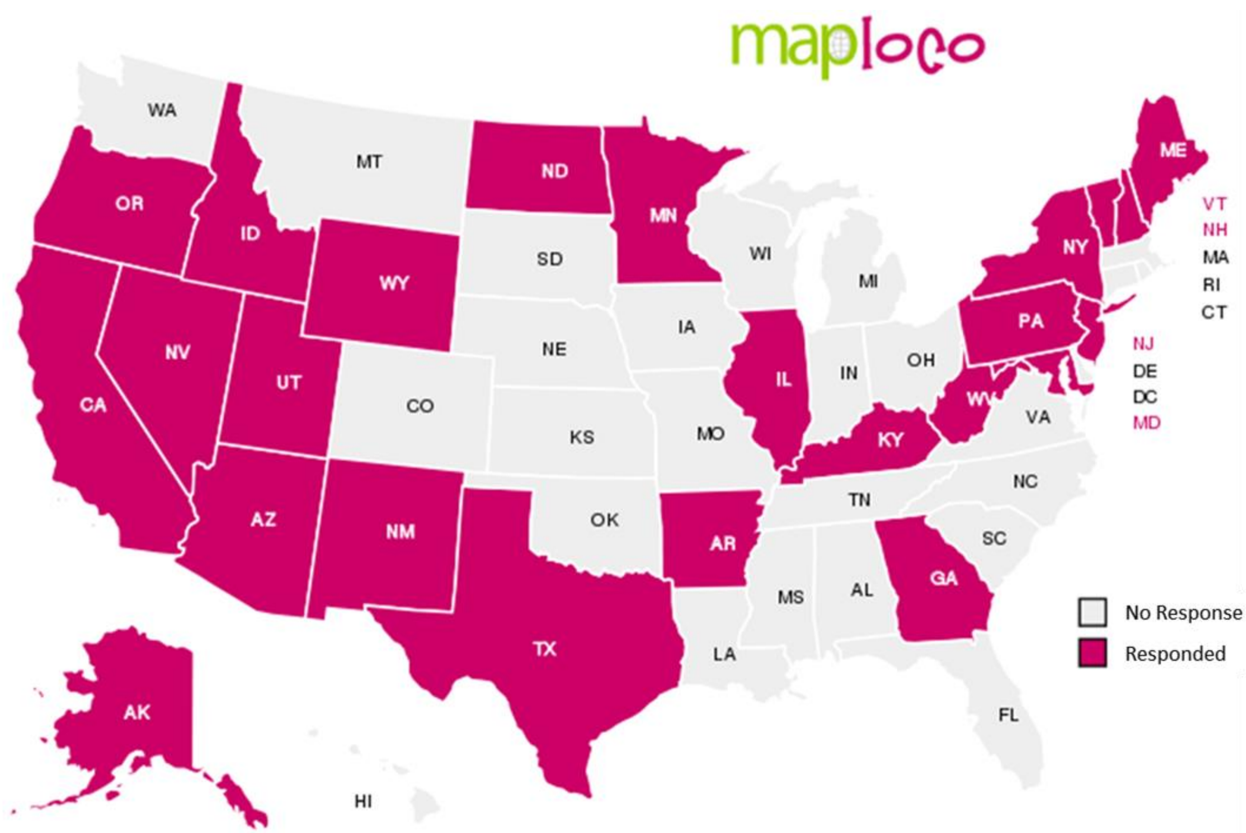


Figure 14: U.S. Survey Respondents (Map Source: maploco.com)

The survey included twenty-one (21) questions related to RWIS use, management, data and planning. A copy of the survey is included in Appendix A.

3.1. Survey Results

The results presented in this section contain all 28 responses, but some results are better presented considering the number of responding agencies. When the number of responding agencies metric is used the two instances of multiple responses from a single agency have been resolved to a single response for the agency.

When asked "***What are the primary and secondary uses for RWIS data in your state/province?***" the respondents communicated the results shown in Figure 15. The complete (unabbreviated) response options are: Winter Maintenance (e.g. snow and ice pre-treatment and removal), Traveler Information, Manual weather warnings posted to static or dynamic message signs (DMS), Weather-responsive ITS applications (e.g. DMS warnings automated by weather sensors), Share data with non-agency weather service providers (e.g. National Weather Service), Weather related performance metrics (e.g. time to bare pavement, time to normal traffic conditions), Aeronautics (e.g. flight planning, storm monitoring/forecasting), and Others (where respondents can write in their own text). The remainder of the document uses abbreviated response options, but the complete options are included in the survey (Appendix A).

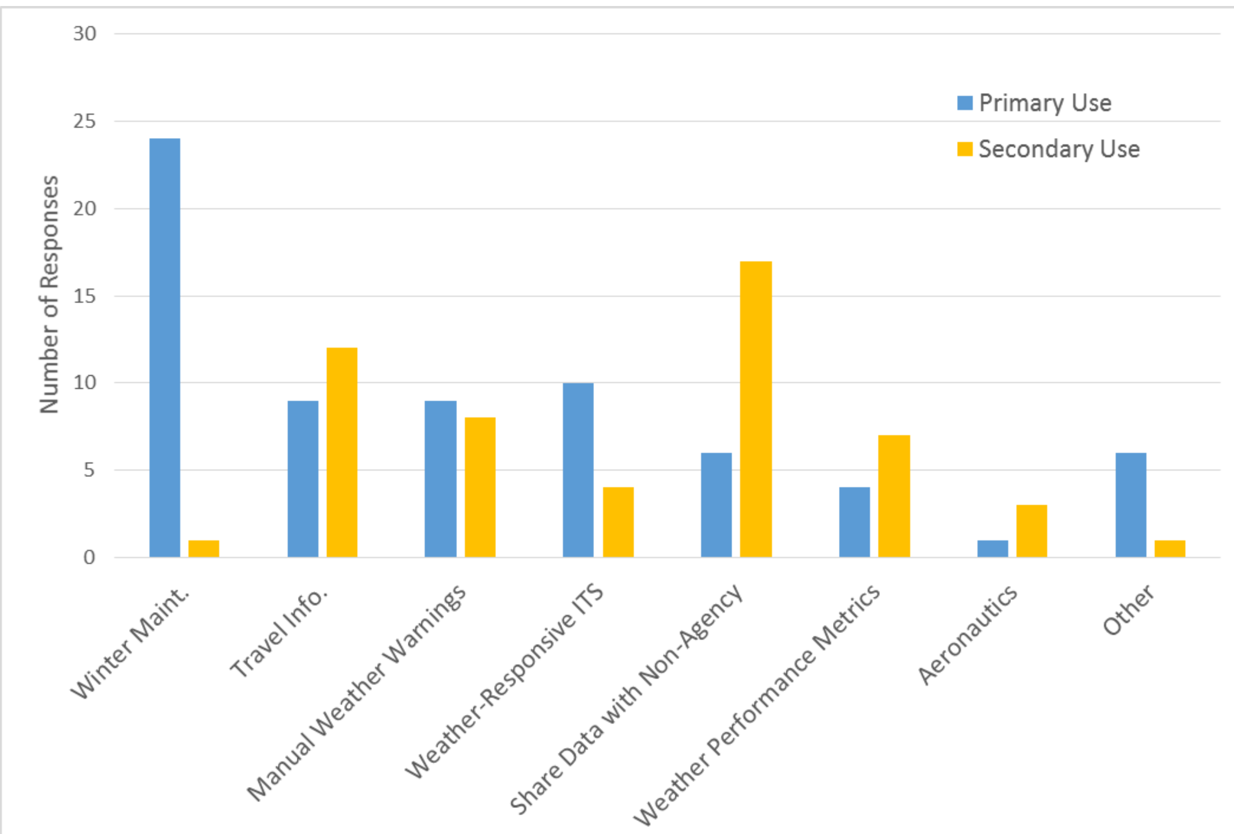


Figure 15: RWIS Data Uses

As expected, winter maintenance activities remain the most common primary use for RWIS data. The next most common primary use for RWIS data is for weather-responsive ITS applications which are becoming more common as technology advances. Other manual weather warning and travel information uses also received multiple "primary use" responses. The most common secondary use of RWIS is for use in sharing data with non-agency weather service providers. Again traveler information was cited multiple times as a secondary use of RWIS data. A few instances of RWIS data use for weather related performance metrics and aeronautics were also observed both for primary and secondary use. A handful of respondents wrote in responses in the "Other" category which included "pavement and weather forecasting", "emergency response such as wild fires, flooding, landslides and burn scars", "avalanche forecasting", and sharing with neighboring states.

When asked "***Do you also collect operational data (i.e. traffic speed, traffic volume, vehicle class, vehicle weight) at RWIS sites?***" the respondents communicated results that are shown in Figure 16.

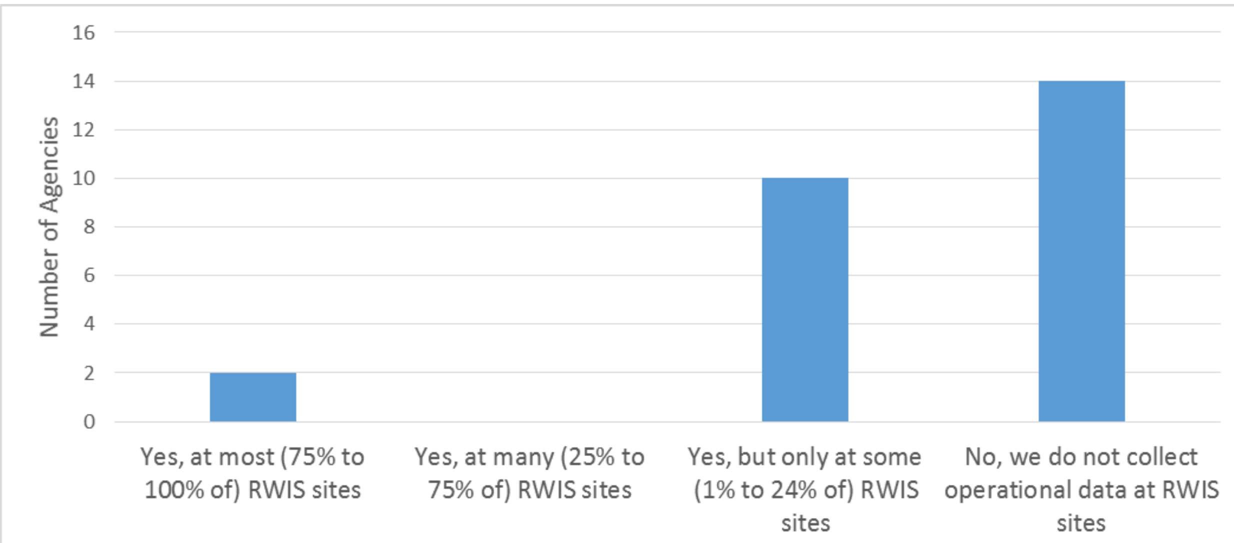


Figure 16: Operational Data at RWIS Sites

Over half (14 of 26) of the responding agencies do not collect operational data (i.e. traffic speed, traffic volume, vehicle class, vehicle weight) at RWIS locations. Ten (10) agencies do collect operational data at RWIS locations, but only at a limited number of their RWIS sites (less than 25% of their RWIS sites). Two (2) agencies collect operational data at most of their RWIS sites (at 75% or more of their RWIS sites). The collection of operational data at RWIS locations can be used to help track weather related performance metrics like the time it takes after a storm to return to normal traffic conditions, a practice that has "growing interest" according to one recent state of practice survey (PB & Iteris, 2013a). The integration of traffic and weather monitoring data in a single location can also allow for weather related ITS applications like those uncovered by Hawkins & Albrecht (2014) including RWIS and traffic data activating warnings on dynamic message signs for foggy conditions and if a related incident has caused slow or stopped traffic ahead.

The survey question "***Do you use any mobile RWIS (weather sensors and/or cameras mounted to vehicles to monitor weather conditions in real-time)?***" yielded results that are shown in Figure 17.

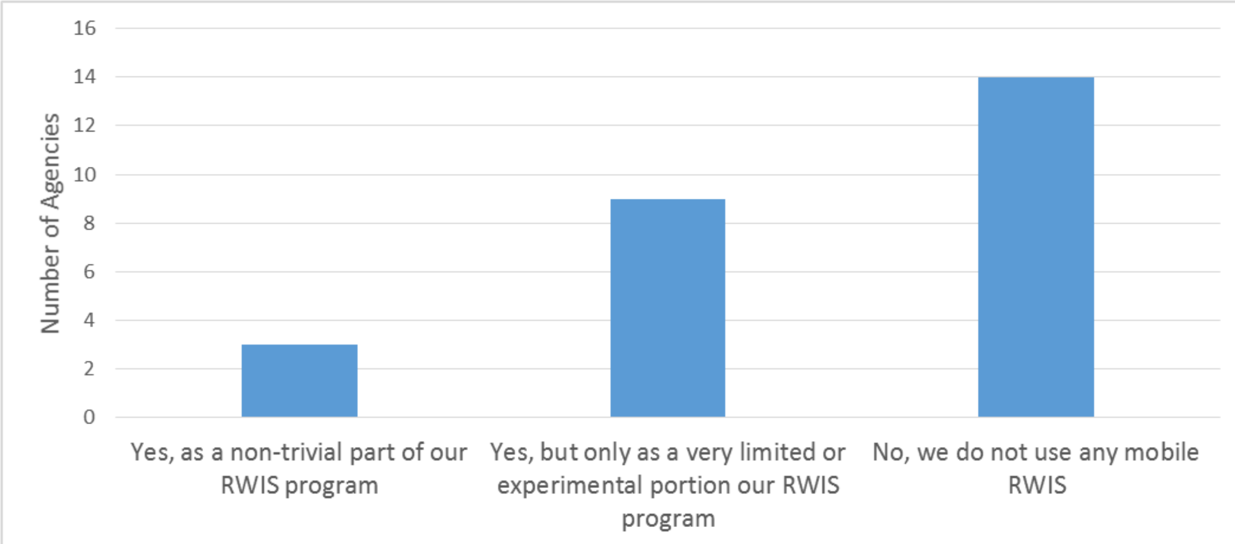


Figure 17: Current Mobile RWIS Use

Most agencies (14 of 26) do not use any mobile RWIS. Nine (9) agencies have very limited or experimental mobile RWIS efforts underway, and three (3) do have more robust mobile RWIS in place.

When asked "***What percent of your current funding / efforts go toward mobile RWIS vs. traditional stationary RWIS?***" the respondents communicated results that are shown in Figure 18.

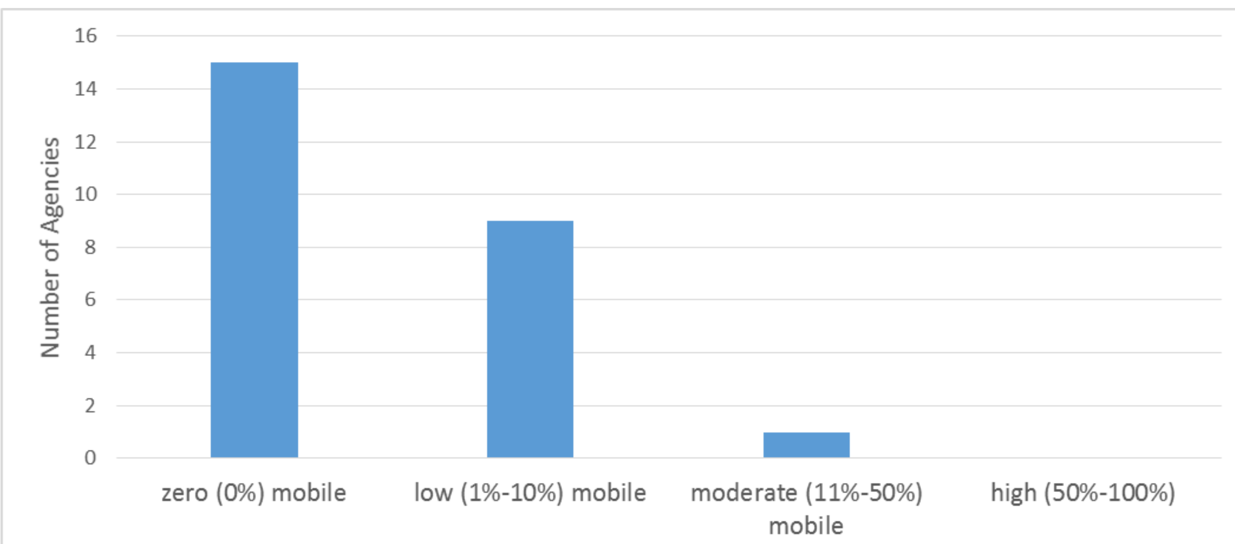


Figure 18: Current Mobile RWIS Funding and Efforts

Most agencies (15 of 25) currently devote no funds or efforts to mobile RWIS. Nine (9) agencies use low funding/effort levels (10% or less) toward mobile RWIS, and only one (1) agency uses more funding/effort (11% to 50%) toward mobile RWIS. One (1) respondent did not know how much funding/effort went toward mobile RWIS.

Figure 19 summarizes the results for the survey question: "***What percentage of your future funding / efforts will likely go toward mobile RWIS vs. traditional stationary RWIS 5 years from now?***".

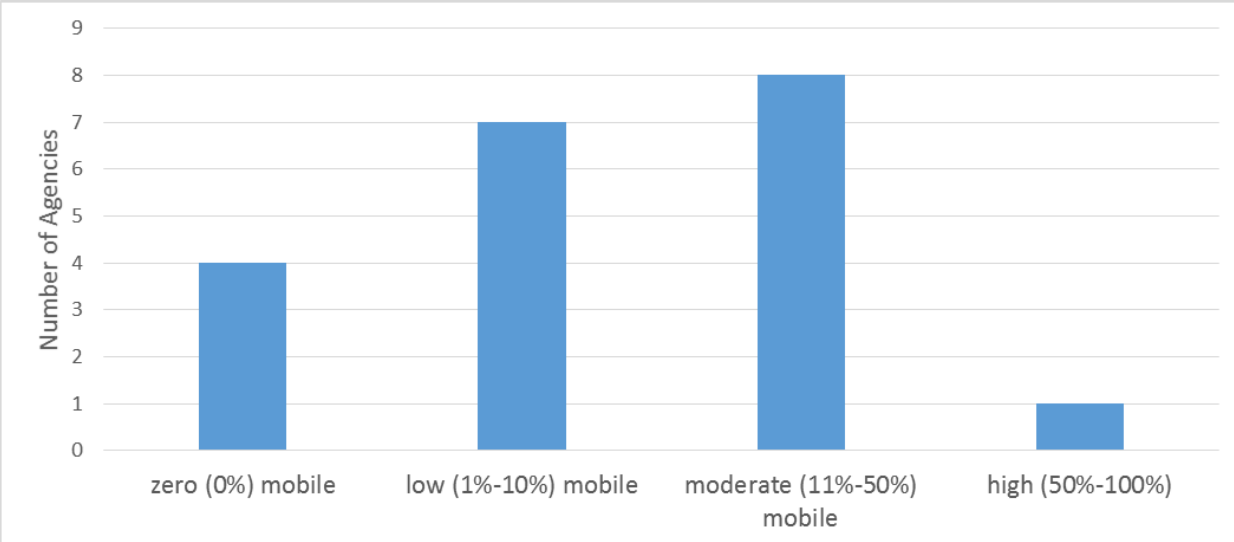


Figure 19: Future Mobile RWIS Funding and Efforts

Many agencies (9 of 20) speculated that 5 years from now they would devote more than 10% of their funding/efforts toward mobile RWIS. One agency even speculated that 50% or more of their future funding may go toward mobile RWIS. Four (4) agencies thought that in 5 years they would continue to devote zero funds/effort toward mobile RWIS, while the remaining 7 agencies responded that 1% to 10% of their future funding/efforts would go toward mobile RWIS. Six (6) agencies did not indicate a response to the question.

Comparing current and future mobile RWIS funding/efforts shows that many agencies anticipate growing mobile RWIS where there are currently none. Also many of the agencies expect it to receive a considerable amount of their overall RWIS funding/efforts (over 10%).

When asked "***Do you incorporate mobile maintenance vehicle data into RWIS (e.g. plow data, spreader data, Canbus data)?***" the results are as shown in Figure 20.

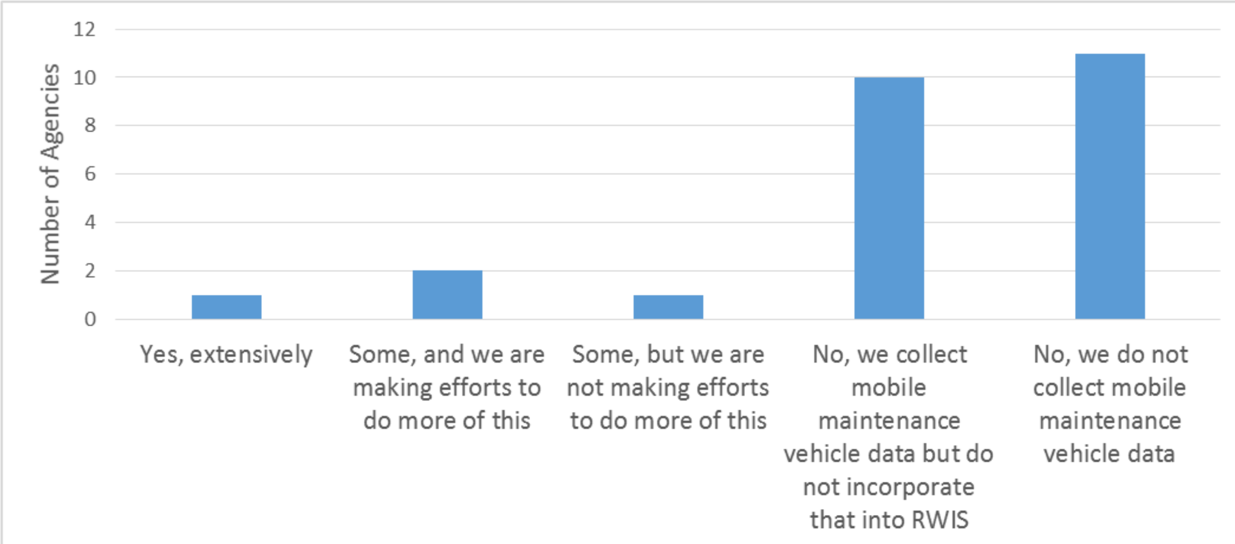


Figure 20: Mobile Maintenance Vehicle Data in RWIS

Many (14 of 25) agencies collect mobile maintenance vehicle data, but only four (4) incorporate mobile maintenance vehicle data in their RWIS. One (1) agency has incorporated the data extensively and two (2) more agencies aim to incorporate more of this data in the future.

When asked "***How have RWIS locations typically been chosen in your agency?***" the respondents communicated results that are shown in Figure 21.

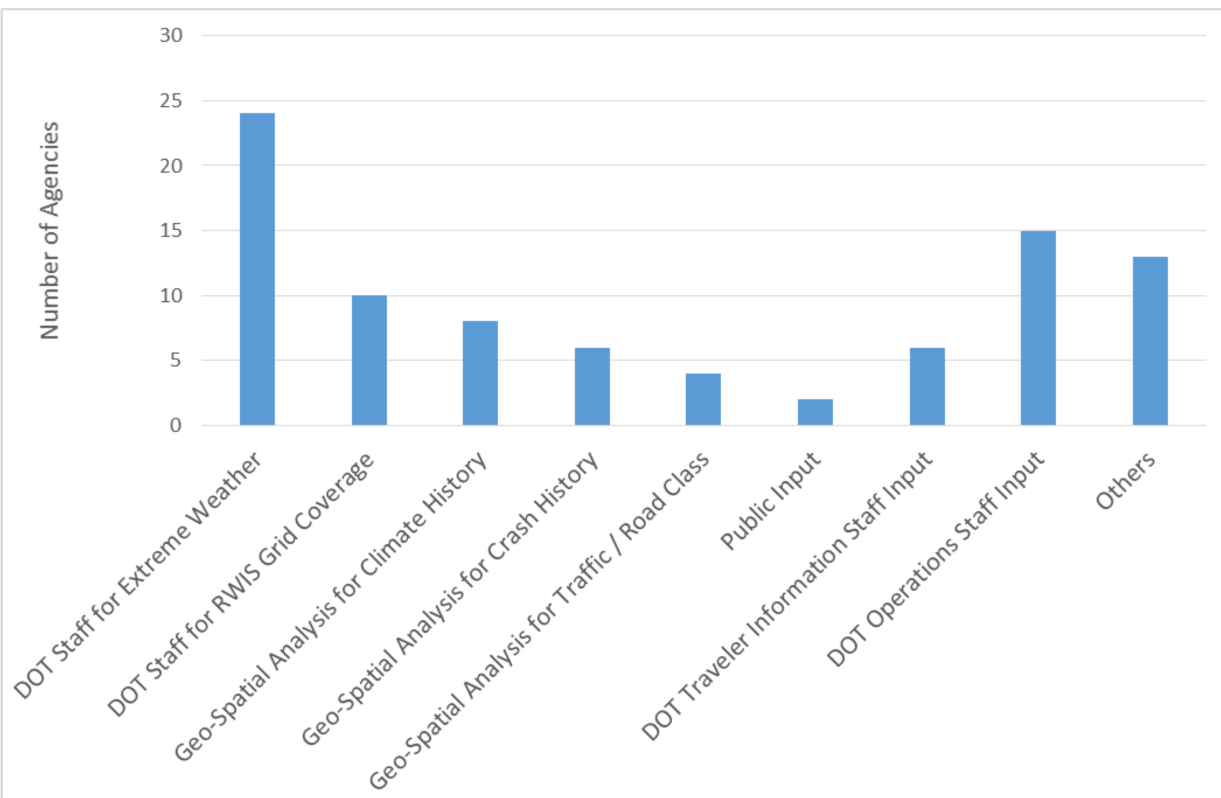


Figure 21: RWIS Placement Methods

The most common RWIS placement method has been to rely on DOT Maintenance staff expertise considering extreme weather locations, followed by considering DOT Operations staff input, as reported by 24 and 15 responding states respectively. Some instances of placement for a grid-type coverage were stated, as well as different geospatial analyses and DOT Traveler Information staff input. Two (2) instances of including public input were also cited. Respondents also wrote under the "Others" category responses such as: placements driven by studies from consultants/academia, placements where power and communications were available, placements at specific challenging locations, placements resulting from thermal mapping analyses, and placements with national weather service input.

When asked to "***Please rank the weather attributes for your uses as one of the following: not necessary, helpful, or must have.***" the respondent communicated results that are shown in Figure 22 and Figure 23.

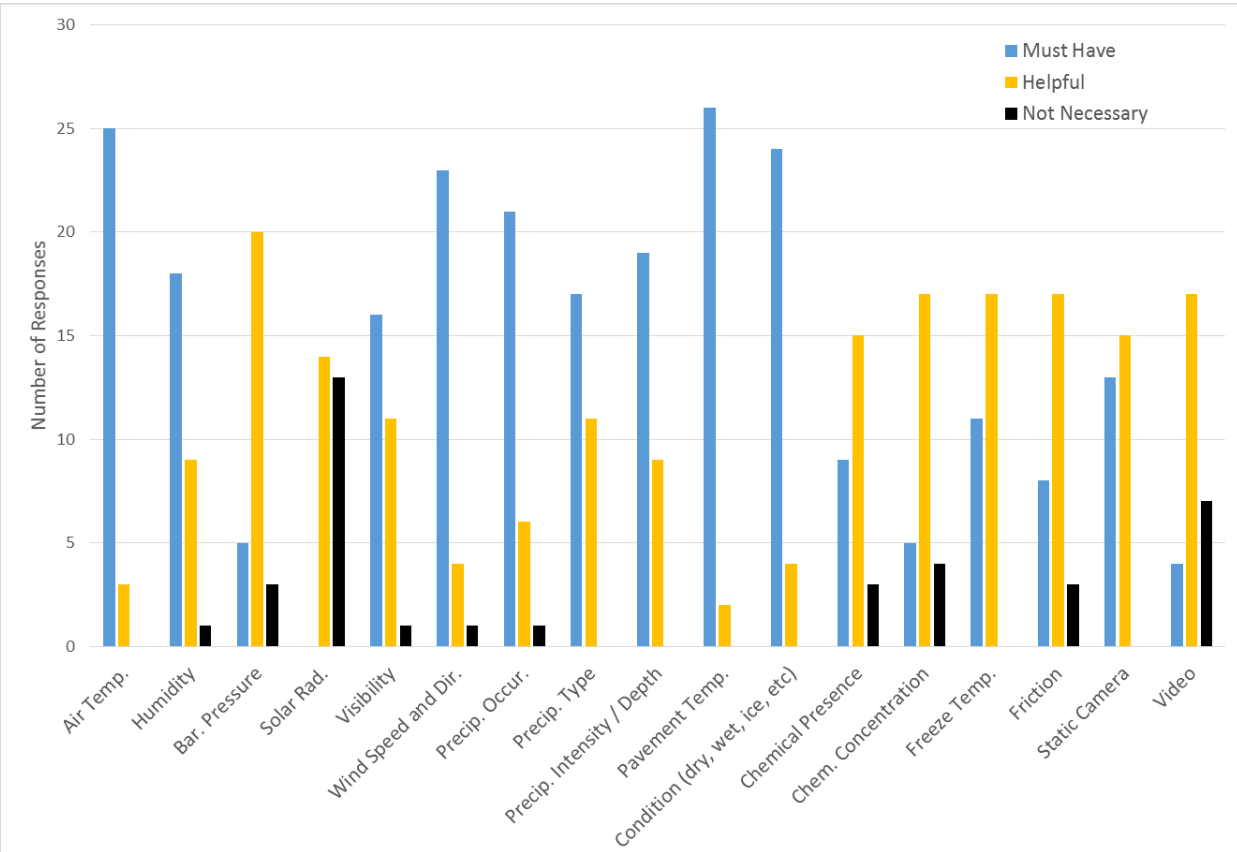


Figure 22: RWIS Data Importance (All Responses)

Many types of RWIS data received "must have" importance for the majority of respondents (14+ of 28) including: pavement temperature, air temperature, pavement condition, wind speed and direction, precipitation occurrence, precipitation intensity/depth, humidity, and visibility.

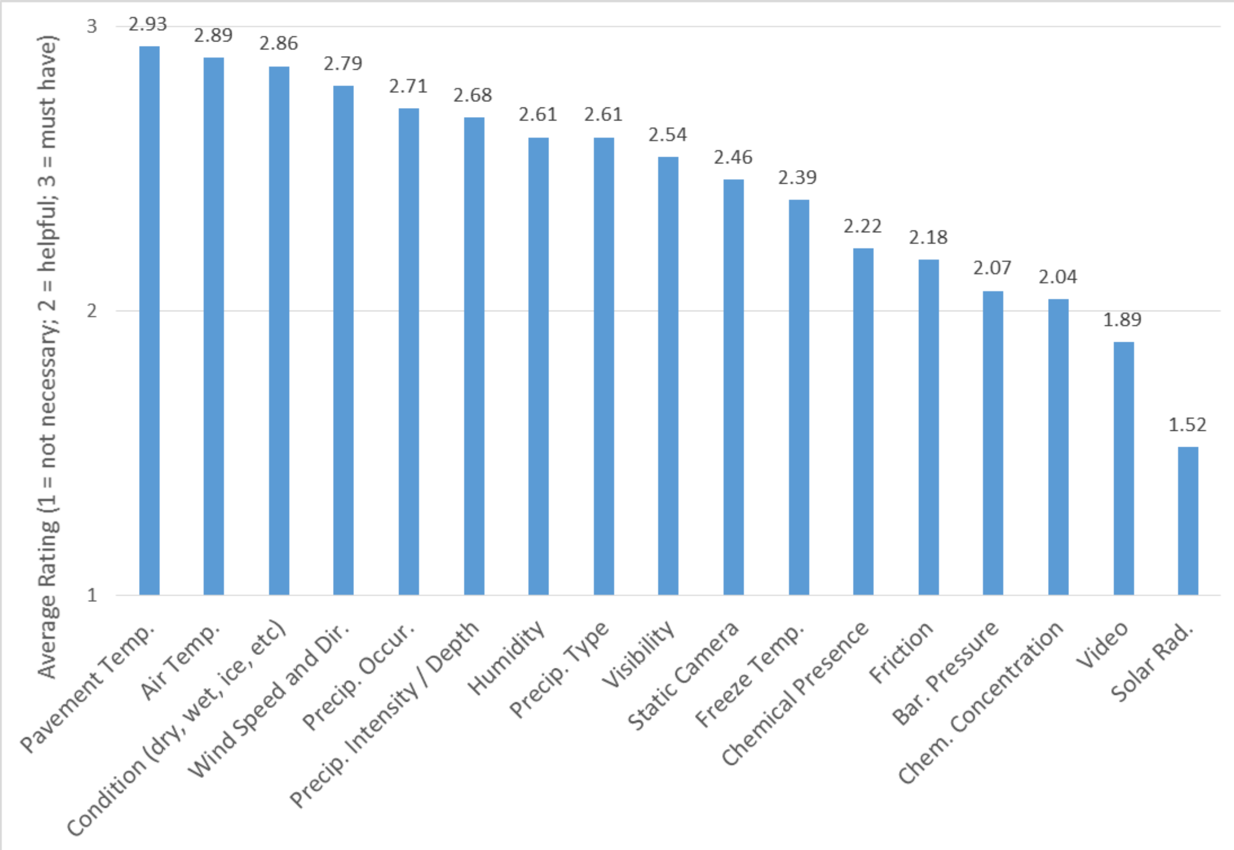


Figure 23: RWIS Data Importance (Ranked Average Ratings)

Using the average rating score with 3 being “must have”, 2 being “helpful”, and 1 being “not necessary”: only two (2) of the RWIS data are found to be rated less than “helpful”: solar radiation and live video.

When asked about the agency preferences regarding “***Open architecture, non-proprietary controllers and communications***” the respondents communicated results that are shown in Figure 24.

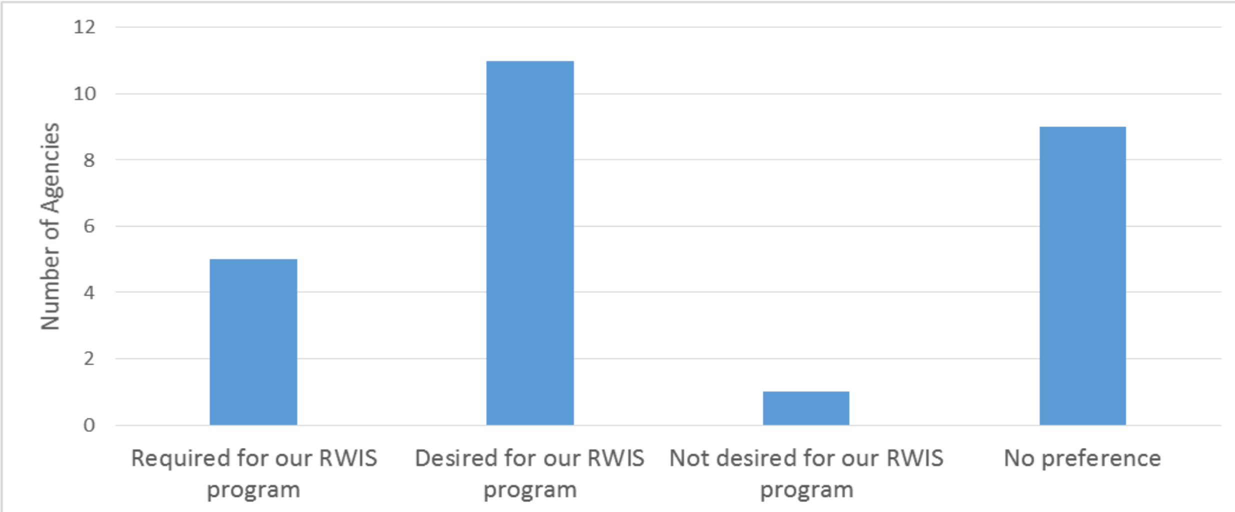


Figure 24: Agency Preferences in Relation to Open Architecture RWIS Controllers and Communications

Most agencies (16 of 26) desire and/or require non-proprietary RWIS controllers and communications. Nine (9) agencies have no preference and one (1) agency prefers vendor controlled proprietary controllers and communications.

Figure 25 summarizes the responses to the survey question regarding the accuracy of ***forecasts provided by RWIS vendors to the agency.***

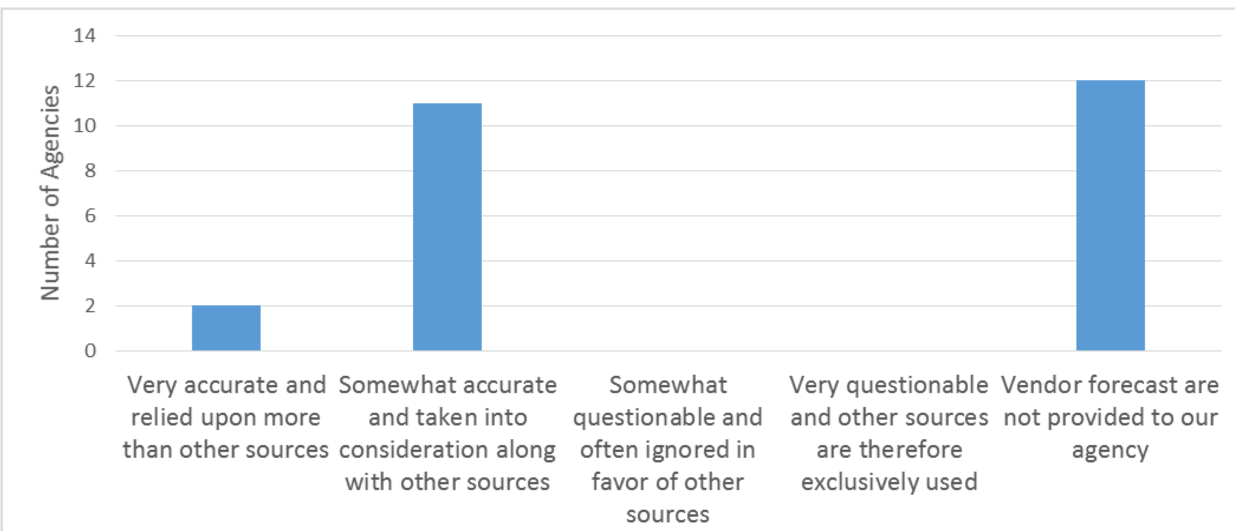


Figure 25: Accuracy of RWIS Vendor Forecasts

Approximately half (13 of 25) agencies receive RWIS vendor forecasts and they all find those forecasts to be at least somewhat accurate and used. Twelve (12) agencies do not receive RWIS vendor forecasts. No agencies report receiving questionable RWIS vendor forecasts which could be an indication that RWIS vendor forecasts are typically accurate or that those agencies that may have received questionable forecasts have since stopped receiving vendor forecasts especially if those services were provided for a fee.

When asked about RWIS program expansion the respondents communicated results that are shown in Figure 26.

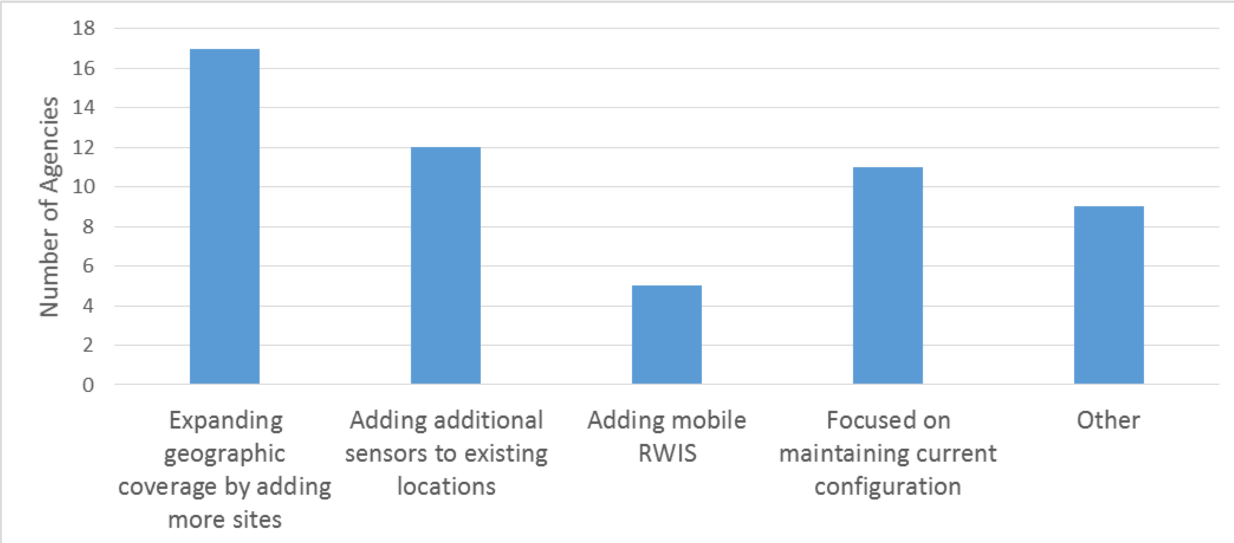


Figure 26: Agency Plans for RWIS Program Expansion

Eighteen (18) agencies are continuing to expand their RWIS by adding more stationary sites. Twelve (12) agencies are adding additional sensors to their existing RWIS sites. Five (5) agencies are adding mobile RWIS. Eleven (11) agencies are satisfied with their RWIS and are focusing on maintaining their current configuration. A handful of written comments in the "Other" category include: "Expanding RWIS integration into ITS projects (automated DMS and Variable Speed Limit systems)", "Hopeful to add stationary units in near future", and "Re-evaluating the role(s) that RWIS/ITS will play in future Maintenance and Traffic Operations".

When given the preamble: "***Balancing costs associated with RWIS sites can depend on many factors, but one aspect is the type and number of sensors at each RWIS site. It has been suggested that certain agency needs may potentially be met with a limited installation (e.g. only a camera and pavement temperature sensor at each RWIS site).***", and then asked about the agency preferences ***if they were tasked with creating an RWIS program from scratch (given today's technology and their current knowledge),*** the respondents communicated results that are shown in Figure 27.

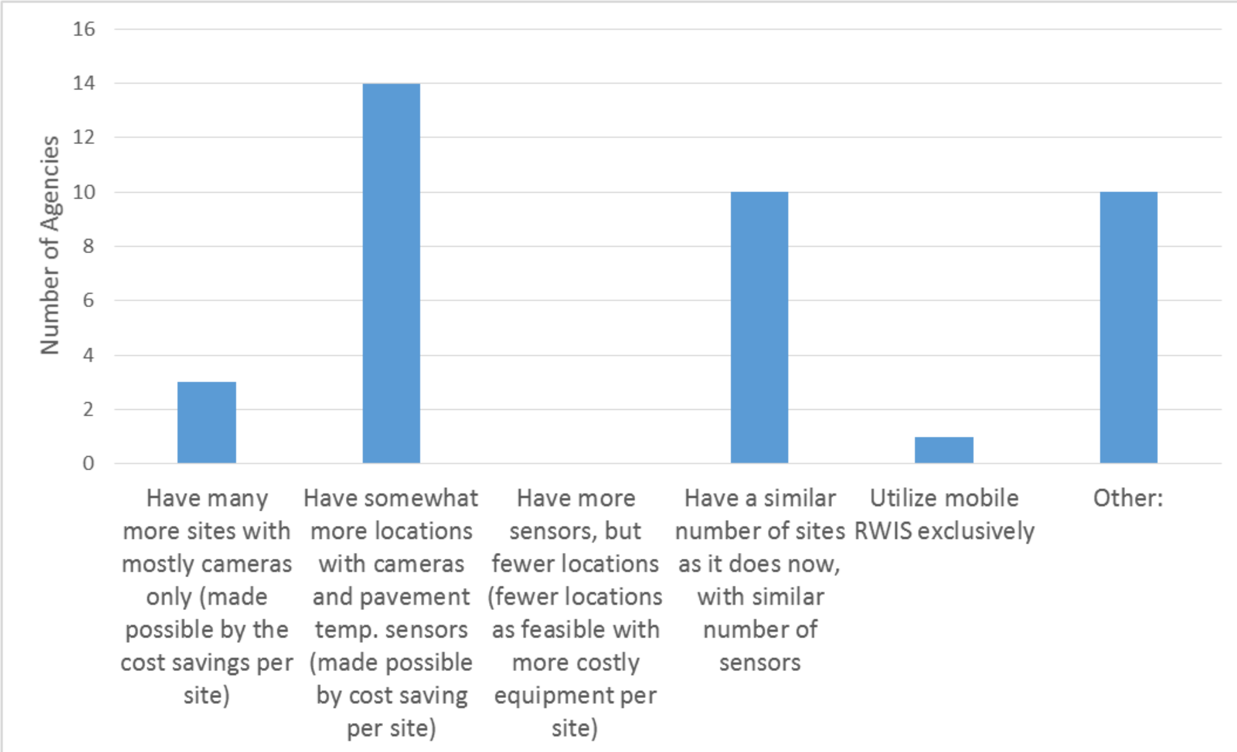


Figure 27: Limited RWIS Site Equipment Feasibility

Many agencies did apparently agree with the premise that more RWIS sites with limited sensors would be better than their current configuration. Specifically, fourteen (14) agencies indicated somewhat more stations with cameras and pavement temperature sensors would suffice, and three (3) agencies indicated that many more stations with mostly cameras only would suffice. Ten (10) agencies feel their current configuration of sites and sensors is the best option. A handful of different considerations were also included in written form in the "Other" category including: "Our new contract is performance based meaning we don't dictate the number and type of sensors, we tell them what data we want", "We are looking at cameras with remote pavement temp sensors", "Somewhat more locations with pavement temp/condition, temp/humid, wind, and camera", "Different sensors, e.g., less precipitation occurrence, more precipitation accumulation", "Provide a service for the public to report road conditions and upload images that are geotagged", and "Have 10-20% more sites than we have now, more cameras, a few less sensors per site than we have now and incorporate/start the use of mobile RWIS".

Figure 28 summarizes the results for the survey question: "***What software do you use to display RWIS data?***"

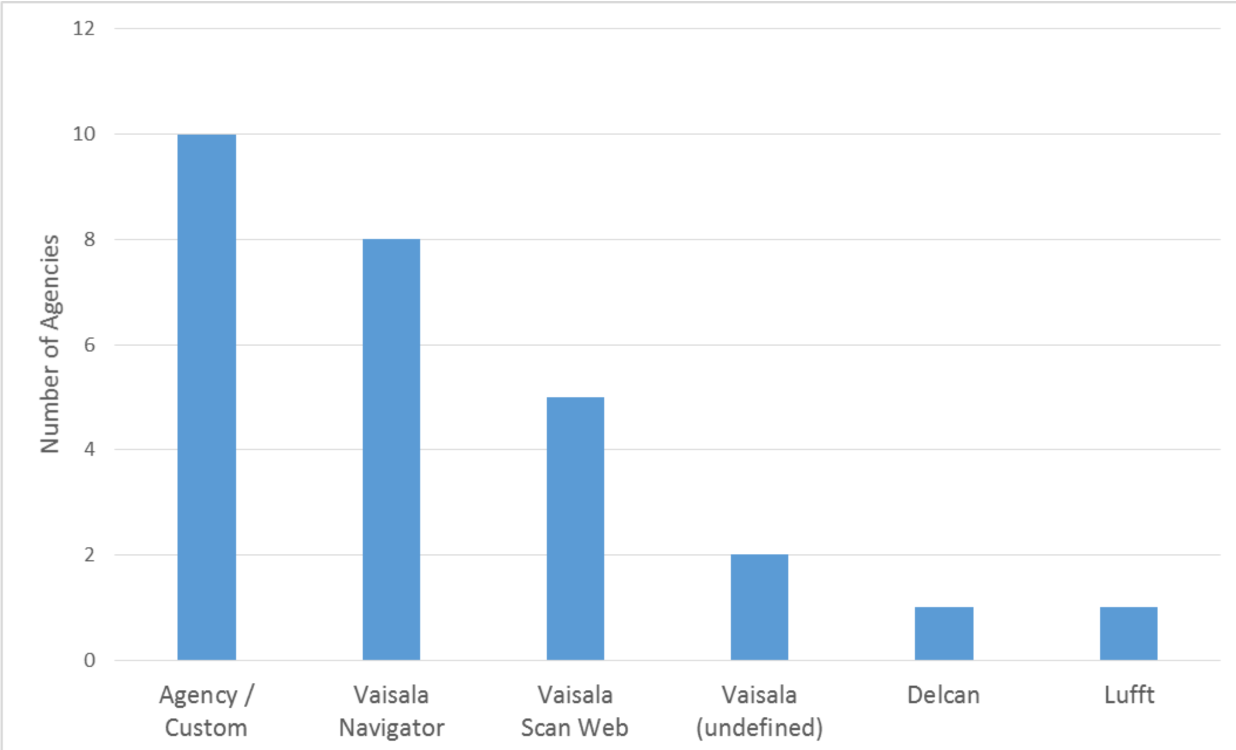


Figure 28: RWIS Data Display Software

Ten (10) agencies use their own custom software to display RWIS data. Eight (8) agencies use Vaisala's Road Weather Navigator software, five (5) use ScanWeb, a software now part of Vaisala, and another two (2) use an unnamed Vaisala software. A couple instances of other RWIS provider software packages were also being used and/or developed: Delcan and Lufft. It was also common to see agencies using a vendor software (like ScanWeb) in addition to their own agency software.

When asked "***Who operates and maintains your RWIS software and hardware?***" the respondents communicated results that are summarized in Figure 29.

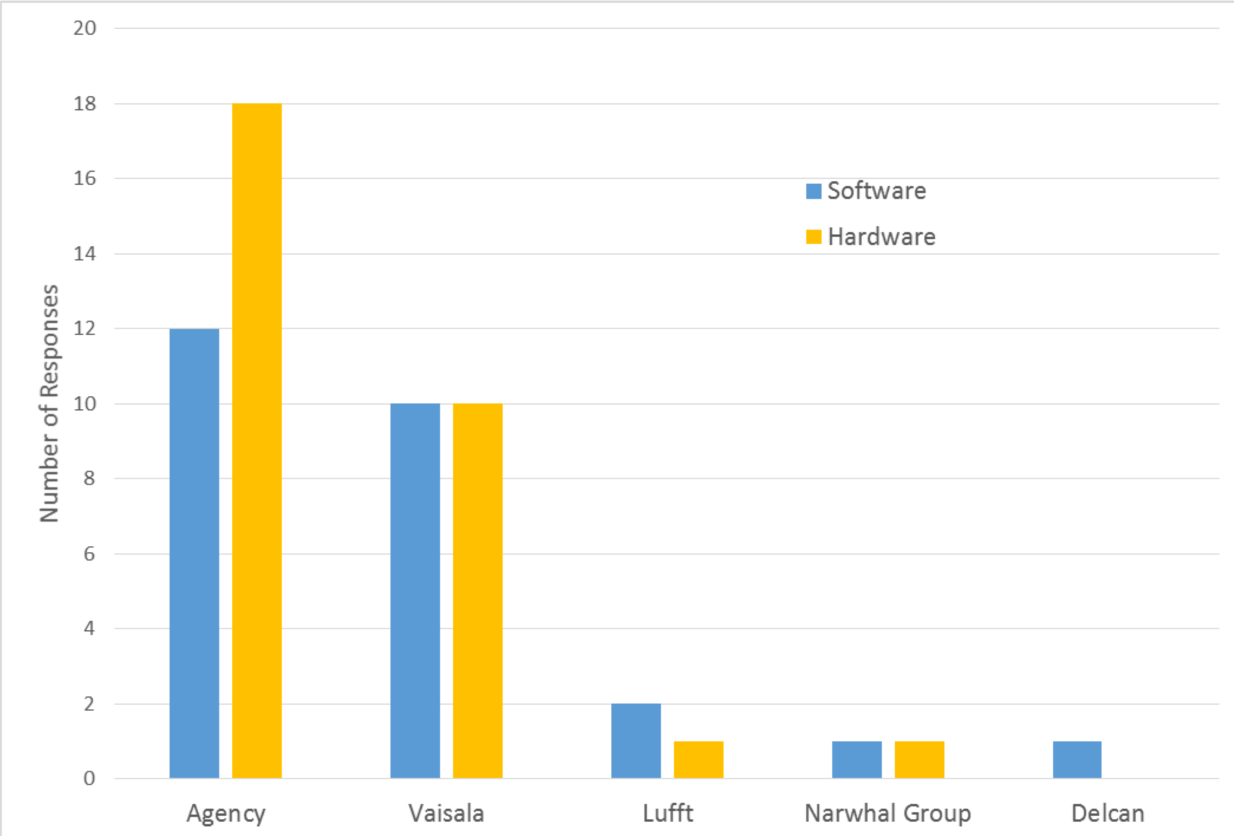


Figure 29: RWIS Software and Hardware Operation and Maintenance

Many agencies maintain and operate their own hardware and software. Vaisala was also cited as operating and maintaining RWIS hardware and software by ten (10) of the responding agencies, which puts the company at the forefront of RWIS service providers in the US. Lufft was reported to maintain the RWIS software for two agencies and the hardware for only one agency. Further, both the Narwhal Group and Delcan were reported to maintain software and hardware for one agency each. It was again common to see agencies maintaining and operating their RWIS hardware and software with assistance from a vendor. Five (5) agencies stated they operated and maintained their RWIS software with vendor assistance and seven (7) agencies stated their hardware operations and maintenance were a mix of in-house personnel and vendor assistance.

When asked "***Are there ways in which you would like to improve upon your current RWIS software?***" many respondents offered comments/ideas that are provided in the following list:

- "Integrate mobile data with fixed data",
- "Expand RWIS alerting service",
- "Display our Winter Maintenance Performance Metric",
- "Filterable data display",
- "Show the last 12 hours with the ability to show more history",
- "The wave of the future is smartphones and the software should be usable by these devices",
- "Mobile friendly",

- “Ability to add more than 2 items to determine if alert is needed”,
- “A general overview of all site data would be nice”
- “Graphical views in which you can overlay multiple sensor data”
- “More historical data on a single page”,
- “Easy navigation between data”,
- “One user need is to calculate precipitation accumulation in the same time bins as NWS”,
- “Performance reporting integrated into Navigator”,
- “Show on a dynamic Google Earth layer and incorporate NOAA and NWS data layers for enhanced reference”, and
- “Mobile device apps”.

When asked “***Are there any aspects of your current RWIS program that you would like to see improved to better meet your needs?***” some agencies described their ideas:

- “Desire non-invasive road instrumentation that can better handle various road types, shallow angles to the road and increase friction sensitivities”,
- “Mobile capabilities will be increasingly more important, especially in determining road condition”,
- “Low powered sensors are a must due to high number of solar RWIS sites”,
- “More pavement sensors”,
- “Complete move to non-proprietary software in the field and at the central data aggregation and display location”,
- “Replacement of in-pavement sensors with out-of-pavement sensors”,
- “Move to an open system to become vendor independent”,
- “The use of more non-intrusive sensors to be independent of any roadway rehabilitation or construction”
- “We're struggling to finance the transition from embedded pavement sensors to optical sensors”,
- “Movement towards mobile sensing capabilities is hampered by the fact that our highway maintenance is contracted out, and it's a hard sell to the contractors”,
- “Would like to see mobile capabilities”,
- “We would like to start implementing mobile RWIS to the system in the near future”,
- “Better remote communication options”,
- “Improved maintenance contract”,
- “GIS frontend”,
- “Performance metrics and health of the network reporting”,
- “Better response from [vendor] regarding requests for quotes/pricing”,
- “More integration with partners who can better post process the data into something beneficial”,
- “Better field hardware”,

- “I'd like to completely replace the Scanweb software and I'd like to create competition for new RWIS sites”,
- “We have needs to upgrade software for better reliability of the data network through cellular communications”,
- “Expand the network through additional RWIS stations”, and
- “Need more flexible data sources through the incorporation of mobile RWIS”.

When asked “***What is the future of your current RWIS program?***” some agencies described their ideas:

- “Additional sites and more integration with ITS. We currently have a project to put all of our RWIS data and camera images into 511 as well as images from our snowplows.”,
- “Pilot testing and evaluation of mobile RWIS”,
- “Adding WiFi communications for uploading snow plow controller data in near real time.”,
- “Significant RWIS upgrades and expansion will be ongoing for five years or longer in support of the [agency] Winter Maintenance Performance Metric. Focus on new installations will be geared towards spatial coverage rather than micro climates. Shed boundaries will try to be avoided unless a microclimate exists.”,
- “Expanding coverage”,
- “Additional sites”,
- “Replacement of in-pavement sensors with out-of-pavement sensors. Replacement of existing field and central systems with non-proprietary software. Addition of more sites over time with locations determined by field Maintenance personnel. Focus on ground truth-ing all sensors yearly for accurate and reliable data.”,
- “Additional sites for ITS and travel info. [Agency] has determined that the public is the driving force and that other agencies can also use the information.”,
- “Status quo”,
- “New sites being installed under construction projects.”,
- “Additional sites, increased integration with ITS, experimentation with mobile optical pavement sensing (using Lufft MARWIS system).”,
- “Want to add/repair more static sites and begin using mobile units within metropolitan areas”,
- “We have a plan to add more sites, update older sites and add camera only sites as well. Mobile sites are something we are interested in doing in the near future. We have started adding traffic speed sensors for performance measures as well.”,
- “Additional sites and integrate with a GIS program to pull [snow and ice coverage] data together in developing dash boards”,
- “Integration as part of the overall ITS Program”,

- "Adding additional sites as needed with more focus on integrating with ITS in certain areas of the state",
- "Improved integration with the existing ITS Program",
- "Additional sites and incorporating LPR and radiation/nuclear detection",
- "Additional sites and more integration with ITS or travel information",
- "Status quo",
- "Status quo",
- "Additional sites. I'd also like to see non-invasive sensors be utilized as we are milling and overlaying too many devices."
- "We are just maintaining the system right now. We are in big need of upgrading the software and data communication system. First generation operating systems and dial up modems are still in many locations. We need to add more cameras and would like to better evaluate/deploy other sensor technologies (non-evasive including friction and freeze pt.).", and
- "Working to gain wider-spread support from maintenance personnel".

3.2. Summary and Key Findings

A large portion of those invited, including approximately half of the agencies in the U.S. and two Canadian Provinces, responded to the survey. Some of the key findings from the survey include:

- RWIS data are now used for many purposes, but remain primarily focused on winter maintenance support.
    - More traditional RWIS data uses like winter maintenance and traveler information are now also joined by many instances of use in weather-responsive ITS and tracking weather-related performance metrics. Unique uses of RWIS data were also found including avalanche forecasting, emergency response, and pavement condition forecasting.
- Operational data like traffic speeds, traffic volumes, and vehicle classifications, are not widely collected at most agencies' RWIS sites, but a couple of agencies do collect operational data at most/all RWIS locations.
    - The collection of operational data at RWIS sites may be necessary if agencies wish to track performance using weather-related performance metrics.
- A few agencies have begun utilizing mobile RWIS as "non-trivial" portions of their program, and many others have begun to experiment with or use limited mobile RWIS equipment.
- Current funding and effort levels toward mobile RWIS remain low overall compared to traditional RWIS, but it is anticipated that a large shift in funding and efforts will go toward mobile RWIS in the next five years.
- Many agencies collect mobile maintenance vehicle data (i.e. plow data, spreader data, Canbus data), but only a few integrate that into their larger RWIS efforts.

- RWIS site placement is most commonly determined using agency personnel expertise, but numerous examples of other methods were cited.
  - RWIS locations have been determined using geo-spatial analyses considering crash histories, climate historical data, and traffic levels / road classifications as well as using public input, academic and consultant research, and thermal mapping analysis.
- Certain RWIS data types were thought to be almost unanimously essential including: pavement temperature, air temperature, pavement condition, wind speed and direction, and precipitation occurrence. Other data types that were thought to be at least helpful on average include: precipitation intensity/depth, humidity, precipitation type, visibility, still camera images, freeze temperature, chemical presence, friction, barometric pressure, and chemical concentration. Live video and solar radiation data were rated the lowest on average in terms of their importance.
- Non-proprietary RWIS controllers and communications were found required by five (5) of the responding agencies and desired in another eleven (11) agencies. As was found in another recent state of practice review (PB & Iteris, 2013), many agencies want non-proprietary systems that allow them flexibility in choosing equipment and products from multiple vendors.
- Overall RWIS programs are still expanding with most agencies adding more sites for additional geographic coverage, many agencies enhancing existing locations with additional sensors, and a handful of agencies adding mobile RWIS.
- In general most agencies support the idea that more RWIS stations with fewer sensors (i.e. camera and pavement temperature only) would be better than their current configurations if made possible by cost savings using fewer sensors per site.
- Agency developed, custom software and Vaisala products are the most common software for displaying RWIS data for the responding agencies, but Delcan and Lufft were also cited.
- Typically RWIS software and hardware are operated and maintained either by agency personnel, by Vaisala, or by a combination of the two. Again, other vendors (Lufft, Delcan and Narwhal Group) also perform these functions in a few responding agencies.
- Respondents were also asked a number of open-ended questions where they could write in their own responses, in which:
  - Multiple respondents emphasized the need for RWIS data display software on mobile devices like a smart phone app.
  - Many respondents stated they would like to see improvements in using more mobile RWIS, more non-invasive sensor technology, and non-proprietary systems.
  - Many agencies are expanding their RWIS programs and many are also pushing for more integration with their ITS Programs.

4) NEEDS ASSESSMENT

This chapter details the methodology and findings of the MDT Agency Needs Assessment task which captures the needs of different agency stakeholders that use RWIS information in Montana. In consultation with the project Technical Panel, the agency RWIS stakeholders were identified. The Maintenance Division is the primary RWIS user and the original developer of the system. Maintenance personnel, especially those responsible for winter maintenance activities, are the primary RWIS data user and as such much of the needs assessment efforts were targeted toward understanding and documenting their needs. Other agency personnel involved with traveler information services and the Aeronautics Division were identified as secondary RWIS data users and were also included in this needs assessment.

Primary Agency Users: Maintenance Division

Multiple methods were used to gather the needs of the primary RWIS users within the Maintenance Division. The first method was a brief workshop type session held during the 2015 Spring Maintenance Chiefs Meeting. This time was used to introduce the project to the Division and begin gathering information on the RWIS needs as expressed by the meeting attendees: Maintenance Chiefs and Supervisors from each of the 10 area offices as well as key Maintenance Equipment, Communications, and Facilities personnel. The next method used was a questionnaire that was sent to each of the Maintenance Chiefs and then forwarded to any Section Supervisors or Maintenance Superintendents that the Chiefs wanted to include. This questionnaire included sections on the responsibilities, practices and decision making of the maintenance personnel, RWIS equipment, software and maintenance and geographic coverage and placement of RWIS stations. A copy of the questionnaire is included in Appendix B. The last method used to understand the RWIS system and needs from the perspective of the Maintenance Division was telephone interviews with key personnel involved with RWIS hardware, communications, and information services/technology.

Secondary Agency Users: Traveler Information and Aeronautics

The secondary RWIS data users were interviewed in order to understand their uses of RWIS and document their needs. A representative of MDT responsible for the traveler information activities of the agency was interviewed as well as a representative of the Aeronautics Division. These telephone interviews were semi-structured with lists of questions helping to guide discussions and follow-up emails used as needed.

4.1. Maintenance Division Uses and Needs

The documented RWIS uses and needs in this section are generated from the workshop-type session, the personnel interviews and especially from the questionnaire which was answered by 33 maintenance personnel including 6 Maintenance Chiefs (MC), 19 Section Supervisors (SS), and 8 Maintenance Superintendents (MS).

4.1.1. Responsibilities, Practices and Decision Making

For the most part, RWIS data helps the maintenance personnel with winter maintenance related activities like snow and ice pre-treatment and removal. However, RWIS data is also used occasionally for practices outside of winter maintenance including: road work projects that may be weather sensitive, issuing high wind and visibility warnings, monitoring and potentially issuing load restrictions during the spring thaw period, and monitoring conditions for weed spraying and road sweeping concerns.

A number of winter maintenance goals and objectives were cited by the questionnaire respondents. Providing safety for the travelling public is the primary mission. Other reported goals included providing a certain level of service and mobility in an economically sensible way without overusing materials that may be costly and impact the environment.

There were no formally documented winter maintenance performance metrics used to monitor and track performance, but a couple of maintenance personnel did say that they do consider the amount of time it takes to return to bare or wet pavement as a sort of informal measure they use to gauge performance.

Winter maintenance decisions are made based on RWIS data as well as other sources of weather information like National Weather Service information and other weather provider forecasts. Figure 30 shows the summary of responses when the maintenance personnel were asked about the percent of winter maintenance decisions that are based on RWIS data compared to other weather data sources. On average, the MCs weighed their winter maintenance decision making as approximately 24% RWIS data driven while the SSs and MSs reported approximately 45% of their decisions being RWIS data driven. These values represent the averages for the response groups with individual responses from MCs varying in the range of 5% to 45% and individual responses from SSs and MSs varying within a 0% to 100% range.

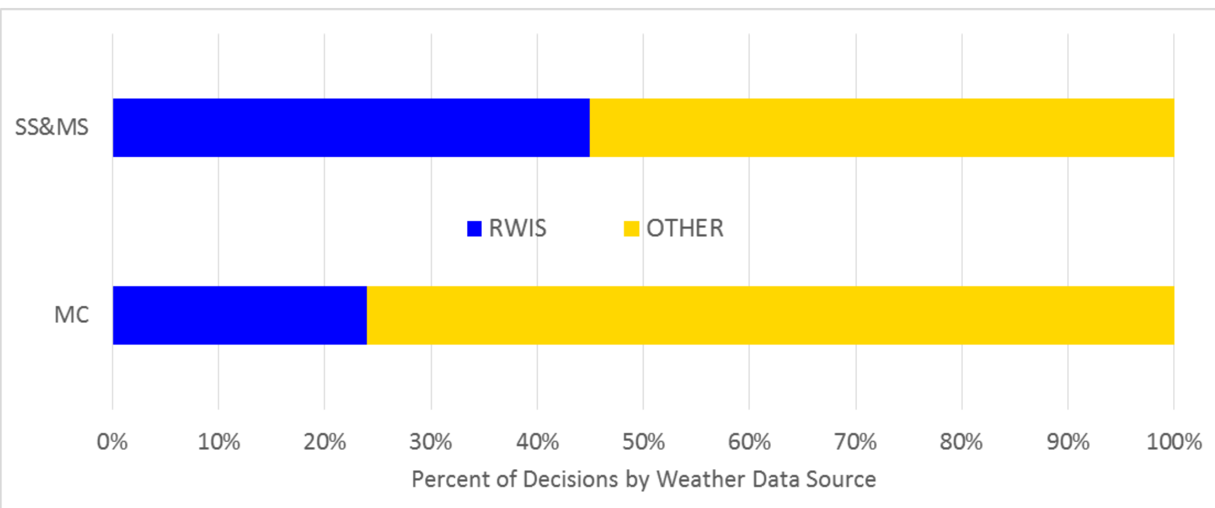


Figure 30: Weather Information for Winter Maintenance Decisions

The main comments related to the use of RWIS data in relation to other sources focused on forecasts. Since RWIS does not currently provide weather forecasts, many maintenance personnel use the other weather information sources that do provide forecasts for planning prior to a storm, then switch and rely on RWIS and/or personnel observations to make decisions during a storm.

4.1.2. Equipment and Software

Various types of weather information are available from many different RWIS sensors and equipment types that are made by different manufacturers. The maintenance personnel were asked to rank the weather information by importance as either “must have”, “helpful”, or “not necessary”. Figure 31 shows the importance of the different weather attributes as reported by the MCs.

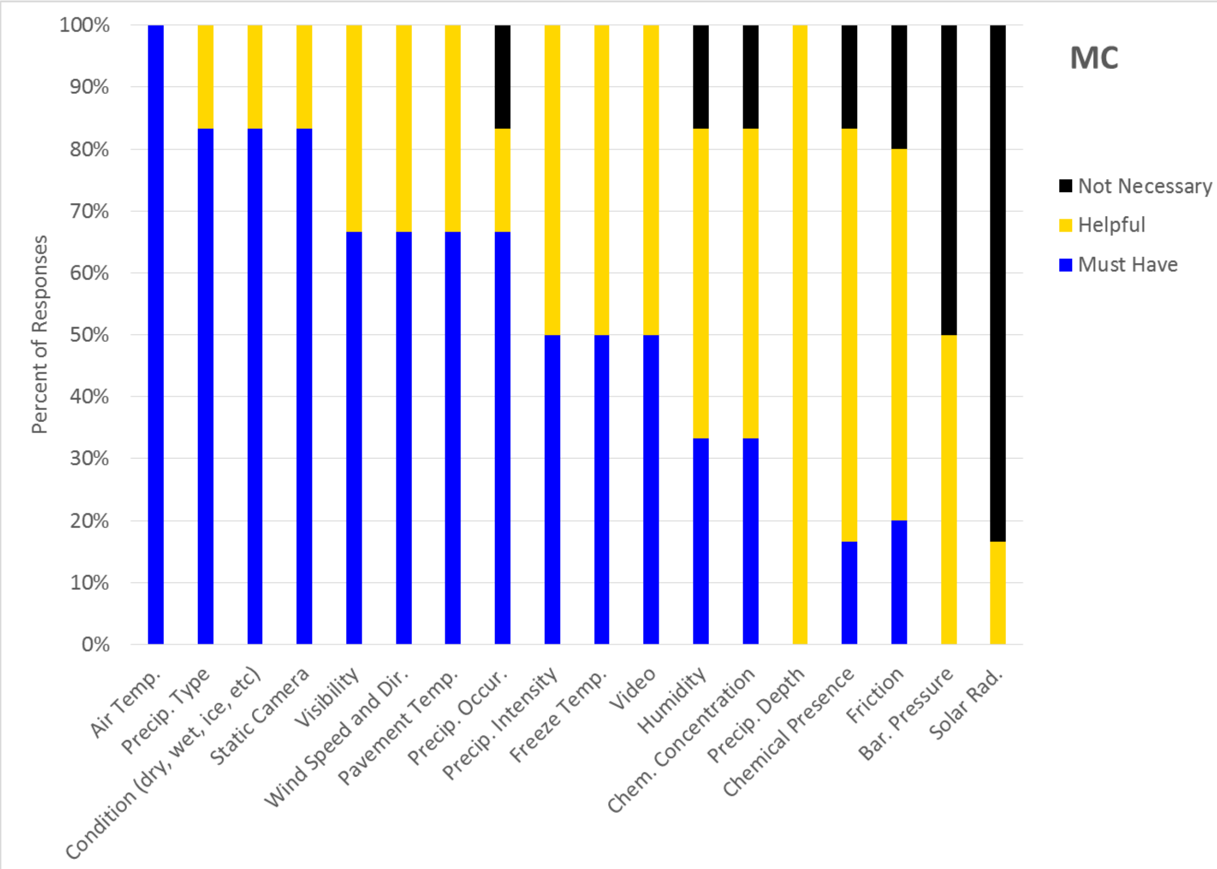


Figure 31: Weather Attribute Importance (Maintenance Chiefs)

The weather attribute importance responses for the SSs and MSs are shown in Figure 32.

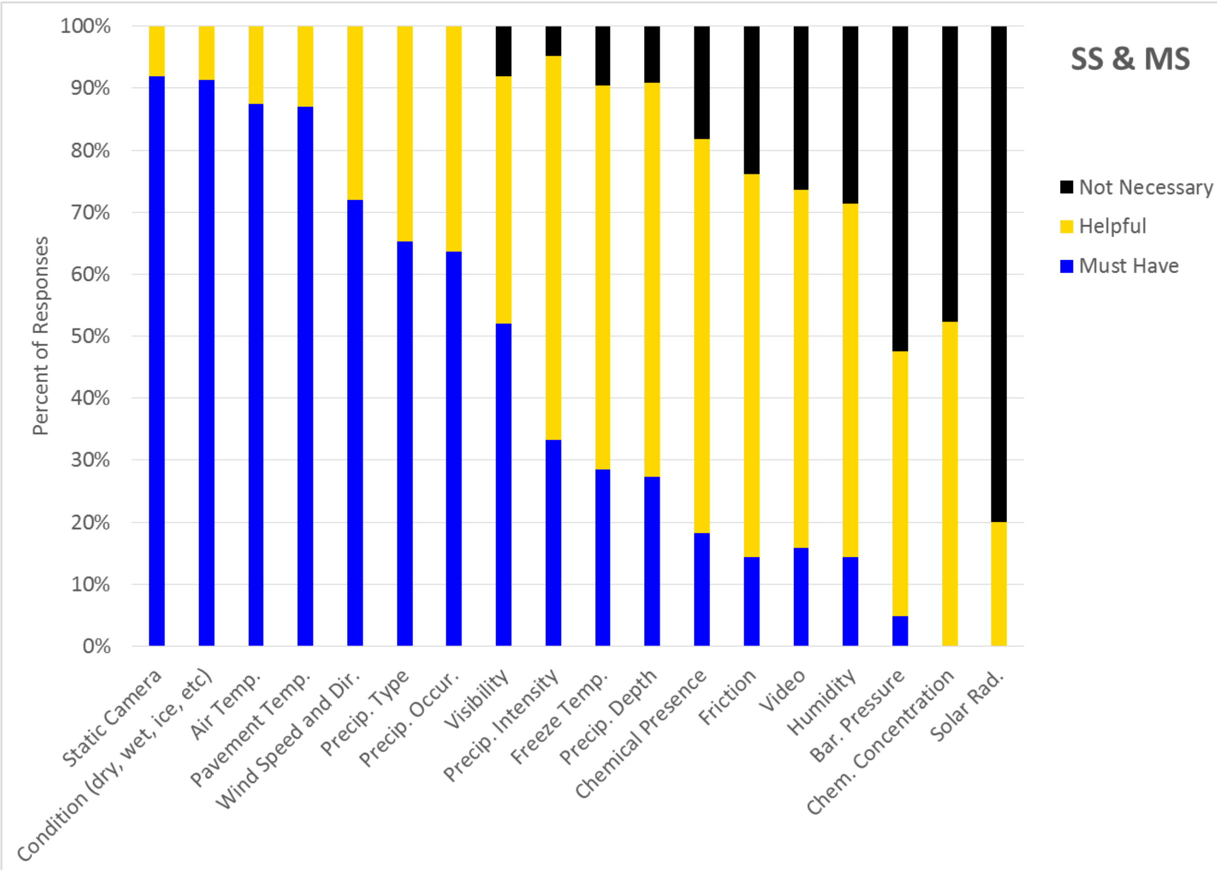


Figure 32: Weather Attribute Importance (Section Supervisors and Maint. Superintendents)

The ranked importance ratings do vary between the two groups (MCs versus SSs and MSs), but for both groups the same 8 attributes that received over 50% of responses as "must have" included: static camera images, pavement conditions, air temperature, pavement temperature, wind speed and direction, precipitation type and occurrence, and visibility.

The maintenance personnel were also asked how often their critical weather attributes should be reported. Figure 33 shows the responses from both groups.

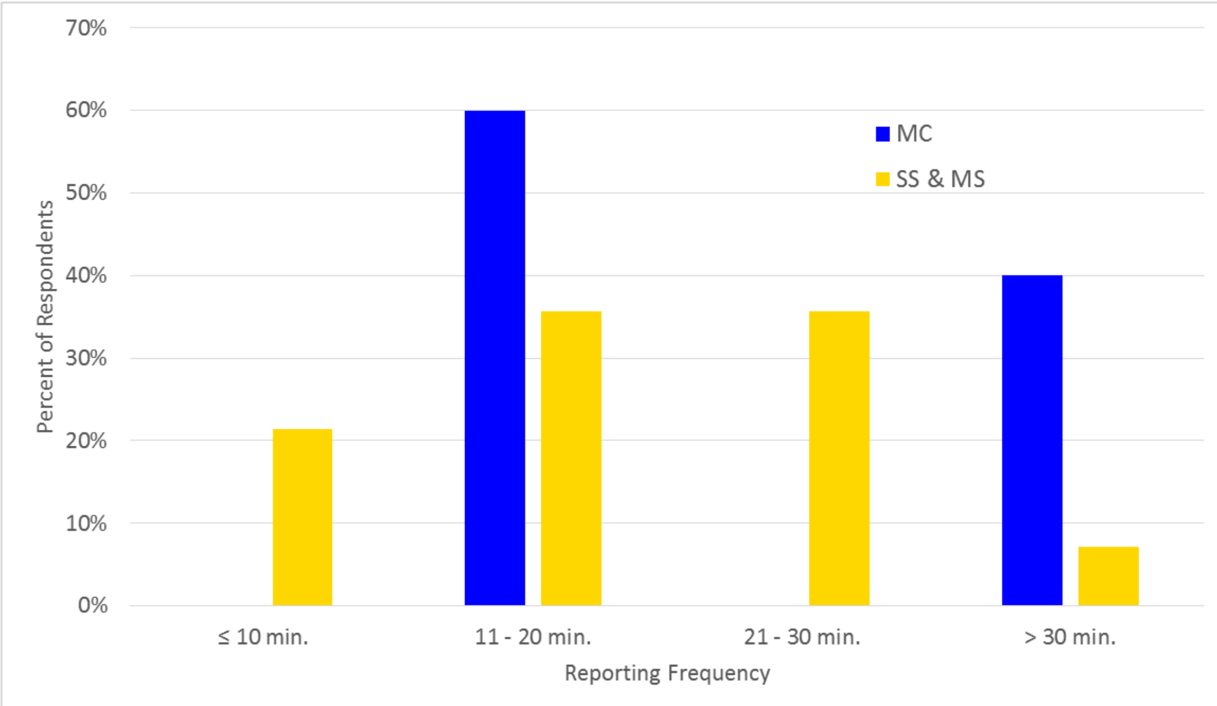


Figure 33: Reporting Frequency

Most respondents indicated they need new data every 15 to 30 minutes, with 15 minutes being the most common response.

For the most part, the maintenance personnel find the current RWIS sensors to be accurate and reliable (17 out of 22 responses). It was also found (during the interview with a key RWIS hardware and communications equipment contact) that when data is unavailable it is usually due to a cellular communications or power issue and not due to individual sensor failures. While maintaining the entire RWIS program, "two to three times a week" a single RWIS site will become unavailable and often require remote diagnostics and repair. MDT technicians spread throughout the 10 area offices are called upon when remote repairs can't remedy the problems.

The maintenance personnel responses indicated that RWIS data communication reliability and timeliness were at times problematic (11 yes reliable and timely, 7 not reliable and timely, 6 sometimes or certain places are problematic). Again the most common issue is with the cellular network. Over 90% of the RWIS sites rely solely on cellular communications and the cellular network provider often has to shut down a cellular tower or block of towers for maintenance or upgrades. These outages are typically without warning and therefore cause RWIS sites to be unavailable for undetermined and unannounced periods due to situations beyond the control of MDT personnel. These outages often last "a few days to a week".

The maintenance personnel felt that currently the RWIS data is updated frequently enough for their needs (16 out of 25 responses). The reporting frequency for the vast majority of the sites is currently 30 minutes.

Approximately half of the maintenance personnel (13 of 25) indicated that they need the sub-surface temperature probes for their duties. These sub-surface temperature probes are often used during the spring thaw season.

The maintenance personnel generally indicated that certain other sensor capabilities are desired:

- 72% of respondents desired non-invasive pavement sensors,
- 82% of respondents desired better precipitation sensors with type, intensity, and depth,
- 87% of respondents desired visibility sensors, and
- 93% of respondents desired improved camera imaging with more pan-tilt-zoom (PTZ) functions and more frequent static images or live video.

Other equipment and software related responses from the maintenance personnel include:

- Static camera images are currently updated enough (19 out of 27 responses).
- Live video is beneficial (17 out of 22 responses).
- Vandalism is typically not a problem (29 out of 31 responses).
- Mobile RWIS sensors are not desired by most SSs & MSs (9 out of 13 responses), but are more desired by MCs (3 out of 5 responses).
- The display of RWIS data on mobile devices is needed (17 out of 22 responses).

4.1.3. Geographic Coverage and Placement

Similar to what was found during the state of the art and practice reviews, previous RWIS placements have been primarily based on MDT personnel experience. Generally the primary users (maintenance personnel) have placed RWIS where they see needs in relation to benefiting winter maintenance activities or addressing known problem areas such as a high wind location or a specific visibility situation near an “alkaline lakebed”. It was also noted that in more recent years, as traveler information has become more popular, the public often voices desires for cameras in certain locations, and those desires are taken into consideration when placing new RWIS sites.

The idea of installing more RWIS sites with limited sensors made possible by the cost savings of fewer sensors per site compared to traditional configurations was uncovered during the state of art and practice reviews. This notion was generally supported by the maintenance personnel (16 out of 20 responses including all 6 MCs supporting) with the understanding that it may be more beneficial to have more coverage with sites having only a camera and temperature probe than fewer traditional sites with more instrumentation. One main caveat was noted however for having wind sensors in addition to the cameras and pavement temperature sensors at high-wind prone locations.

4.1.4. Maintenance of RWIS Software and Equipment

The overall maintenance of the RWIS equipment, communications, and software is performed by a handful of key personnel stationed at MDT headquarters and a number of technicians spread across the state in the 10 area offices.

Currently around half of the RWIS sites in the state have PTZ cameras. These PTZ cameras tend to give a better view of the overall weather conditions than a single fixed view as they take 3 to 4 images at different positions every minute. However, the cameras are the one piece of equipment most prone to failure, and the PTZ cameras tend to fail more often than fixed cameras.

From a maintenance perspective the approach to utilize more RWIS sites with just a camera and pavement temperature sensor could be somewhat more challenging than the traditional RWIS sites approach. This may be the case because the cameras in particular tend to be the most common equipment prone to failure and presumably the more sites, the more frequent would be the typical cellular-related communication failures

A service-based RWIS provider contract was another approach uncovered in the state of the art and practice reviews. Under such an approach, an RWIS provider would be under contract to provide certain RWIS data at certain levels of reliability. This approach was unpopular among the maintenance personnel and the key personnel interviewees, mainly due to poor past experience relying on RWIS providers (for RWIS equipment maintenance, not data delivery). In the early 2000s, when many of the RWIS sites were new a performance based maintenance contract was tried that relied on an RWIS provider. The RWIS provider was largely unable to provide adequate and timely maintenance, especially considering the travel required for a company based in another state to the many possible and often remote RWIS locations across Montana. The agency has since taken over maintaining their entire RWIS program, which is not a trivial task and requires the agency resources that are geographically spread across the state in the 10 area offices.

The software architecture involved in gathering and disseminating the RWIS data from across the state also requires a considerable amount of effort to maintain and that maintenance was also problematic under the previous provider contract. Somewhat recent required software and server upgrades have had impacts on the RWIS program including the loss of certain alerting functions based on changing weather conditions and the loss of the ability to scan the RWIS system for unresponsive sensors at RWIS sites. The alerting and scanning functionality was built on the older software versions and would require new software to be programmed to re-gain that functionality for the new software versions. Unresponsive or malfunctioning equipment are often reported by maintenance personnel or the public who notice the errors on the traveler information websites or mobile apps.

4.1.5. Other Comments, Needs, and Ideas for Improvement

The maintenance personnel were also asked some open-ended questions about including anything not addressed in other questions and any other ideas for improvements they may have. The most common comments from these questions include:

- Real-time and more frequently updated data and camera images would be ideal.
- More RWIS sites are desired, especially at maintenance section boundaries.
- Cameras that provide images in the dark and live video would be beneficial.

Note that under the current cellular communications service plan there is a fixed data amount that is shared by the RWIS sites, so the ability to gather more frequent or live data (or video) may be limited or more costly at the present time.

4.2. Traveler Information Personnel Uses and Needs

The RWIS data and camera images are provided to the public via the traveler information website and mobile app from MDT. The RWIS data is also used by the 511 provider to help create route specific forecasts for the public that call the 511 telephone number for traveler information. The traveler information website and mobile app are used "very frequently" by the public. Some maintenance personnel also utilize the traveler information mobile app since it provides much of the RWIS data they use that is not otherwise readily available in a mobile friendly format.

The public tends to provide a lot of feedback on the traveler information made available by MDT. When sensors, cameras, and sites are unavailable the public typically informs MDT fairly quickly. Also the travelling public often voice their desires for more cameras in specific locations. They have also begun to ask for cameras that can provide images in the dark.

The traveler information services and the travelling public (based on traditional feedback) would tend to favor the potential approach of having more RWIS sites with just a camera and temperature sensor compared to fewer fully instrumented sites. Their only concern with such an approach would be that of being able to keep up with the maintenance of more sites, as they are aware of the maintenance challenges from the frequent public feedback.

4.3. Aeronautics Division Uses and Needs

The Aeronautics Division of MDT often makes flights around the state especially to the 15 state-owned and 125 public-use airports for various inspections, meetings, and improvement grant related activities. The Division's pilots (and pilots from the general public) use the RWIS data and especially certain cameras when planning a flight. Camera images are valuable to pilots if they include a view of the horizon. Similar to surface transportation, aviation decisions often hinge upon the conditions at key mountain pass locations. For example if a camera with a mountain pass horizon view shows poor visibility or low clouds then a flight may be postponed for safety concerns.

The most important types of data for aviation were said to be the camera images, wind speed and direction, visibility and air temperature. RWIS data is not the primary source of data for aviation decisions, but does add valuable information (especially camera images) in certain locations.

4.4. Summary and Key Findings

A number of key RWIS uses and needs have been communicated by MDT stakeholders throughout this needs assessment process including:

- Maintenance personnel need camera images, pavement conditions, air temperature, pavement temperature, wind speed and direction, precipitation type and occurrence, and visibility.
- All Stakeholder groups generally favor the idea of having more sites with only a camera and pavement temperature sensor compared to fewer sites with more sensors per site.
    - Maintenance personnel may also need wind sensors or visibility sensors only at certain locations.
- It may be beneficial to update camera images and RWIS data every 15 minutes.
- The most problematic pieces of equipment (PTZ cameras) are also the most valuable.
- Cellular communications are the main source of outages and those outages are largely out of MDT's control.

- There are certain sensor and camera technologies that may be desired including non-invasive sensors, more robust precipitation sensors, visibility sensors, live video, and cameras with the ability to produce images in the dark.
- The ability to display RWIS data for maintenance personnel on mobile devices is desired, but may be partially available currently via the traveler information mobile app.
- More RWIS sites are desired overall and especially near maintenance section boundaries.
- Mobile RWIS are not generally desired at the SS and MS level, but more interest is shown at the MC level.
- Required RWIS software and server upgrades have recently resulted in some specific functionality losses.
- RWIS data is widely used by the public via the traveler information systems from MDT.
- The public (via traveler information) may be the most common method for the agency to learn of unavailable or malfunctioning sensors or RWIS sites.
- Cameras are the most popular type of information for the public who would presumably prefer more camera-only sites compared to fewer fully-instrumented sites.
- RWIS is a secondary data source for the Aviation Division and general aviation uses in Montana.
- Camera images with horizon views and especially those near mountain passes may be the most valuable RWIS information for aviation.

5) WEATHER DATA AND SOFTWARE ANALYSIS

This chapter details the weather data and software analysis task which establishes an overview of the current system, identifies gaps in the current system compared to the needs of the agency, and identifies and analyzes potential alternatives that may best meet the needs of the agency.

Note to readers: this chapter requires investigation into commercially available products, and efforts were made for the investigation to be inclusive of all potential alternatives available in North America. The reader should be aware that information regarding the capabilities of RWIS hardware, sensors, and software is often only available from the manufacturers and vendors themselves and is not necessarily verifiable by any unbiased sources.

5.1. Current System Configuration

MDT currently operates 73 individual RWIS sites that consist of ESS, hardware and software that are used to process, display and disseminate road weather information in a format that can easily be interpreted by various users. Figure 34 shows the location of the 73 RWIS sites.

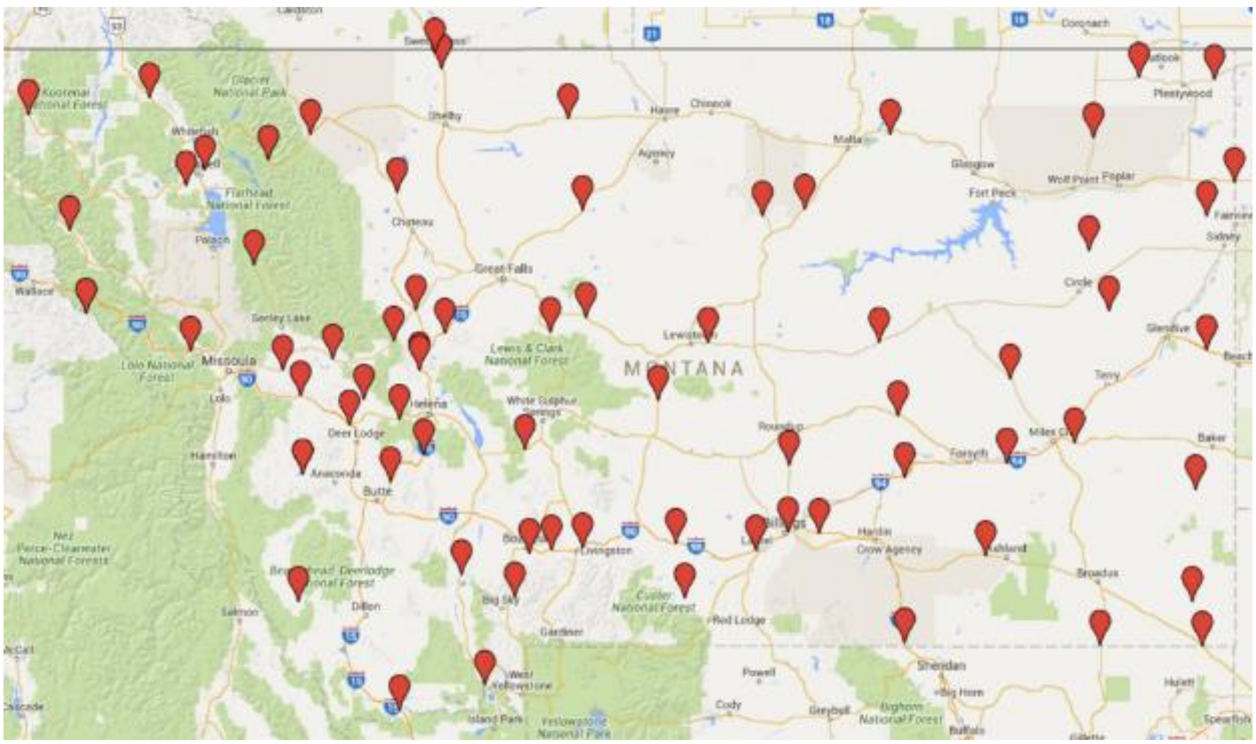


Figure 34: MDT RWIS Sites (Map Source: Google Maps)

These RWIS stations provide the data that are ultimately utilized by MDT Maintenance personnel tasked with winter maintenance activities around the state. The RWIS data are also provided to the travelling public by MDT via agency traveler information websites and mobile applications. A third party vendor (Iteris) also uses the RWIS data as part of systems related to the 511 telephone service. The National Oceanic and Atmospheric Administration (NOAA) also makes use of the RWIS data for the National Weather Service (NWS) and the Meteorological Assimilation Data Ingest System (MADIS). The Western Transportation Institute (WTI) at Montana State University (MSU) also uses MDT RWIS data as part of two larger multi-state corridor travel information and operations management systems. This section outlines the high-level RWIS system architecture, more detailed configurations of the individual ESS, and the current software used as part of the overall MDT RWIS.

5.2. System Architecture

A high-level system architecture showing the MDT RWIS program and associated uses is shown in Figure 35.

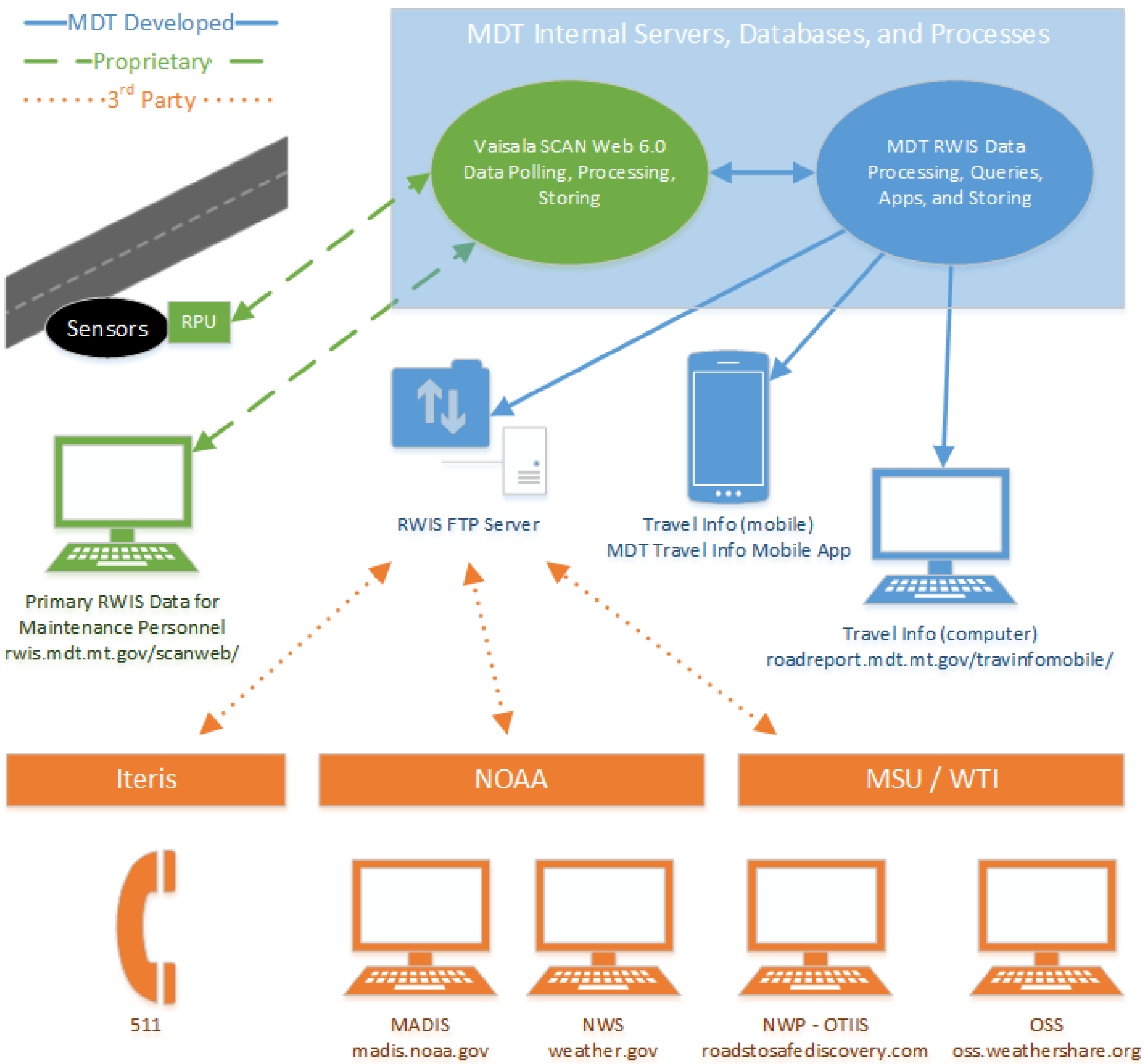


Figure 35: System Architecture

The sensors, cameras, and remote processing units (RPU) in the field at the 73 RWIS stations are owned by MDT. The sensor and camera data are stored locally at each of the RPUs which are then polled by proprietary software (part of Vaisala SCAN Web 6.0) housed at MDT which also processes and displays the data for the primary user group, MDT Maintenance personnel. MDT also has many internal processes, queries, applications, and storage functions that allow for publishing the RWIS data to the travelling public via MDT traveler information websites and mobile apps and to third party users via a RWIS file transfer protocol (FTP) site.

5.3. ESS Configurations

All 73 ESS at RWIS locations essentially have the same core sensor array with a small number of ESS having additional or more advanced sensors than the typical setup. All ESS are grid powered except for five solar powered sites. All ESS use cellular communications except for seven sites that use landline communications due to cellular coverage issues. The core sensor setup that exists at virtually all ESS includes the following hardware, sensors, and associated weather information:

- Air Temperature & Humidity Sensor (Thies or Vaisala) for
    - air temperature,
    - relative humidity, and
    - dew point temperature.
- Wind Speed and Direction Sensor (RM Young) for
    - wind speed and
    - wind direction.
- In-Pavement Sensor (Vaisala) for
    - pavement temperature and
    - surface condition (dry, wet, snow, ice, chemical, etc.).
- Subsurface Temperature Sensor (Vaisala) for
    - subsurface temperature.
- Precipitation Sensor (Vaisala) for
    - precipitation occurrence (yes / no).
- Camera (Axis, Cohu, or Mobotix) for
    - static camera images.
- Remote Processing Unit, RPU, (Vaisala) for
    - sensor reading, processing, and local storage.
- Cellular Modem (AT&T or Verizon) for
    - communication.

The non-core sensors that exist at limited locations to improve the capabilities of the ESS include:

- Advanced Precipitation Sensor (Optical Scientific Inc. or Vaisala) for
    - precipitation type with intensity or rate (at 6 sites).
- Visibility Sensors (Optical Scientific Inc. or Vaisala) for
    - visibility (at 4 sites).
- Infrared Illuminator for
    - nighttime camera images (at 6 sites).

5.4. Software

MDT maintenance personnel primarily use the Vaisala SCAN Web 6.0 software to view RWIS data and camera images on an internet browser (rwis.mdt.mt.gov). This software, while viewable on mobile devices, seems developed primarily for use on a larger computer screen. As such, some maintenance users monitor RWIS conditions and cameras via the MDT Travel Info mobile application.

SCAN Web allows maintenance personnel to view the most current sensor readings and camera images organized into tables by geographical region or on a map based layout of the state with selectable individual stations (see Figure 36).

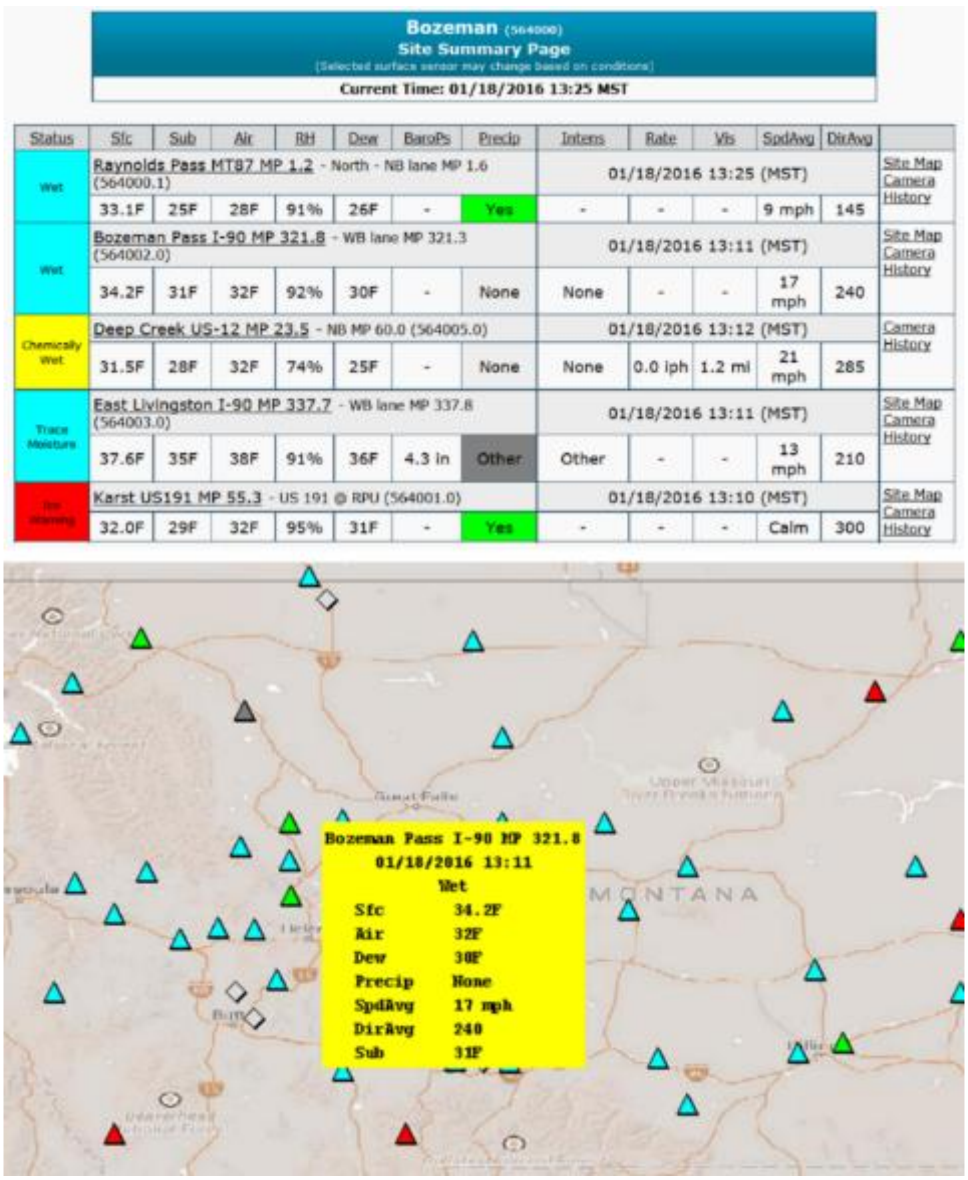


Figure 36: SCAN Web RWIS Data by Geographic Region (top) and Map Based (bottom)

A detailed site status is also available showing the most recent RWIS data with the most recent camera image(s) and information about the last precipitation period observed (see Figure 37).

Kalispell
Essex US2 MP 179.9 (628000)
Site Status

Current Time: 01/18/2016 13:28 MST
Data Time: 01/18/2016 13:15 MST

Air Data						Wind Data			
Temp	RH	Dew	WtBlb	Min	Max	SpdAvg	SpdGst	DirAvg	DirGst
35F	92%	33F	34F	30F	36F	Calm	Calm	180	157

Precipitation			Last Precipitation Period		Accumulation					
Type	Intensity	Rate	Start Time	End Time	10 min.	1 hr.	3 hr.	6 hr.	12 hr.	24 hr.
None	None	-	01/18/2016 13:05	01/18/2016 13:09	-	-	-	-	-	-

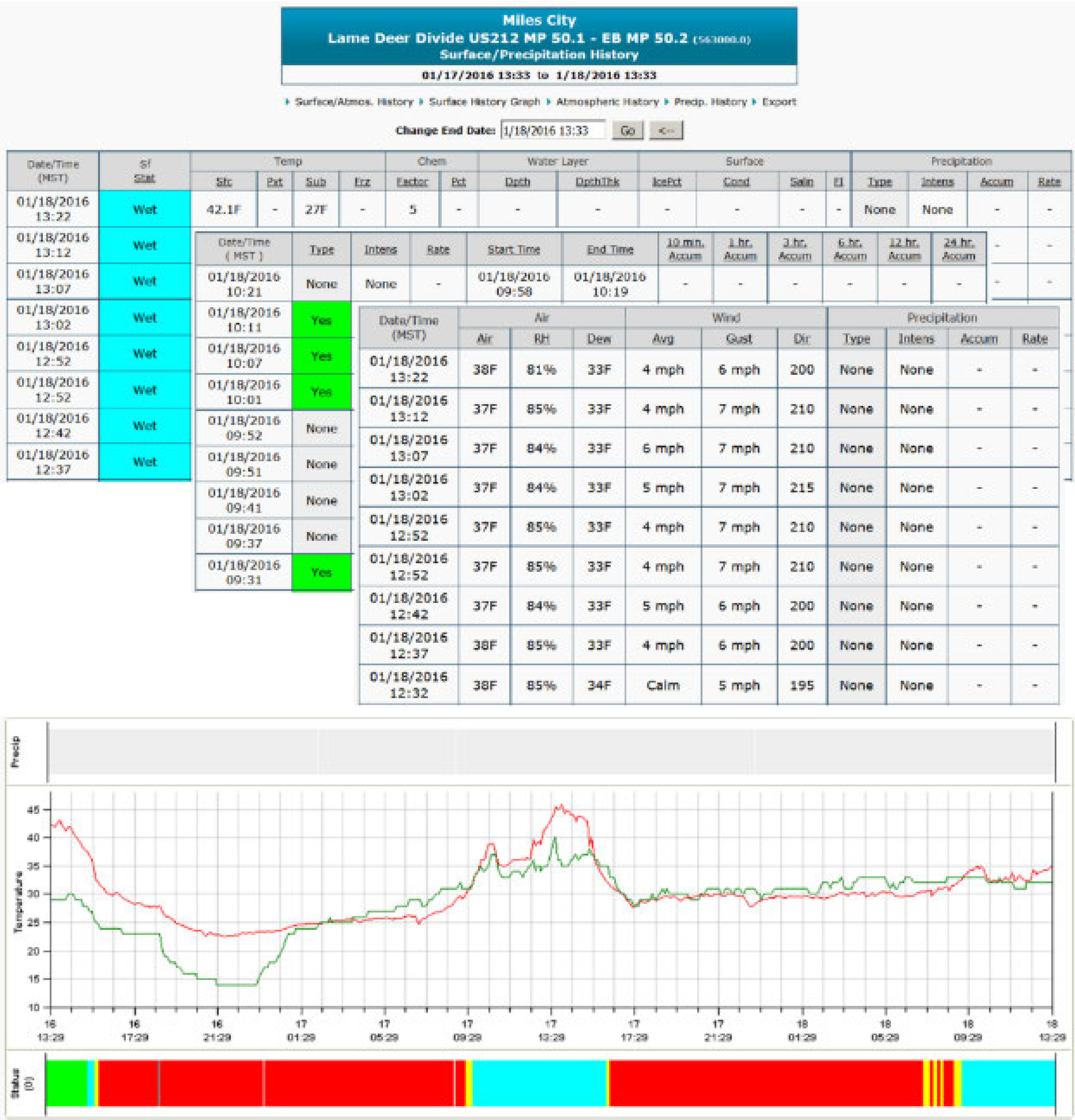
Surface Data														
Sensor	Status	Sfc	Pvt	Sub	Frz	CF	Chem	Dpth	DpthThk	Ice	FI	Cond	Salin	
Bridge Deck - WB lane MP 179.5 (0)	Wet	35.1F	-	28F	32F	95	0%	0.10 in	-	0%	-	1 mhos	123	History

Subsurface Data		
Sensor	Temp	
Subsurface @ 18 (0)	28F	History

North Elev 3875
01/18/2016 13:14

Figure 37: SCAN Web RWIS Site Status

Histories of data from the sensors are also viewable in table or graphical form for periods up to 48 hours in duration (see Figure 38).



Date/Time (MST)	Sf Stat	Temp Sfc	Temp Pvt	Temp Sub	Temp Frz	Chem Factor	Chem Pct	Water Layer Dpth	Water Layer DpthThk	Surface IcePct	Surface Cond	Surface Salin	Surface FI	Precipitation Type	Precipitation Intens	Precipitation Accum	Precipitation Rate
01/18/2016 13:22	Wet	42.1F	-	27F	-	5	-	-	-	-	-	-	-	None	None	-	-
01/18/2016 13:12	Wet															-	-
01/18/2016 13:07	Wet															-	-
01/18/2016 13:02	Wet																
01/18/2016 12:52	Wet																
01/18/2016 12:52	Wet																
01/18/2016 12:42	Wet																
01/18/2016 12:37	Wet																

Date/Time (MST)	Type	Intens	Rate	Start Time	End Time	10 min. Accum	1 hr. Accum	3 hr. Accum	6 hr. Accum	12 hr. Accum	24 hr. Accum
01/18/2016 10:21	None	None	-	01/18/2016 09:58	01/18/2016 10:19	-	-	-	-	-	-
01/18/2016 10:11	Yes										
01/18/2016 10:07	Yes										
01/18/2016 10:01	Yes										
01/18/2016 09:52	None										
01/18/2016 09:51	None										
01/18/2016 09:41	None										
01/18/2016 09:37	None										
01/18/2016 09:31	Yes										

Date/Time (MST)	Air	RH	Dew	Wind Avg	Wind Gust	Wind Dir	Precipitation Type	Precipitation Intens	Precipitation Accum	Precipitation Rate
01/18/2016 13:22	38F	81%	33F	4 mph	6 mph	200	None	None	-	-
01/18/2016 13:12	37F	85%	33F	4 mph	7 mph	210	None	None	-	-
01/18/2016 13:07	37F	84%	33F	6 mph	7 mph	210	None	None	-	-
01/18/2016 13:02	37F	84%	33F	5 mph	7 mph	215	None	None	-	-
01/18/2016 12:52	37F	85%	33F	4 mph	7 mph	210	None	None	-	-
01/18/2016 12:52	37F	85%	33F	4 mph	7 mph	210	None	None	-	-
01/18/2016 12:42	37F	84%	33F	5 mph	6 mph	200	None	None	-	-
01/18/2016 12:37	38F	85%	33F	4 mph	6 mph	200	None	None	-	-
01/18/2016 12:32	38F	85%	34F	Calm	5 mph	195	None	None	-	-

Figure 38: SCAN Web RWIS Site History Tables (top) and Graph (bottom)

A detailed site map graphic is also available for each location to show details of the sensor locations relative to the roadway with their current measurements (see Figure 39).

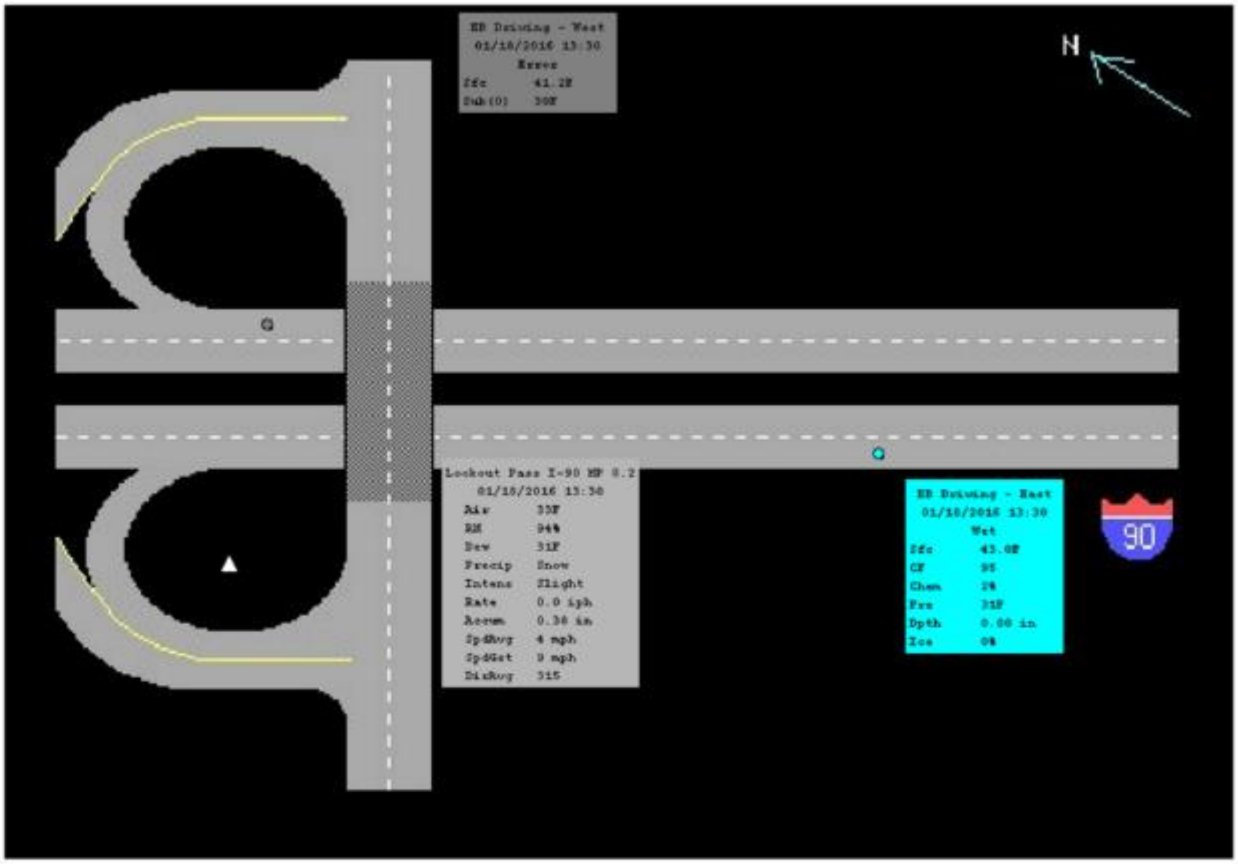


Figure 39: SCAN Web RWIS Site Map

The MDT Travel Info mobile application provides RWIS data and camera images along with other traveler information and is targeted for the traveling public. Some maintenance personnel use this mobile application to view current camera images and RWIS data which are presented on the mobile device primarily using a map display (centered on user GPS location) with selectable RWIS stations. Figure 40 shows the MDT Travel Info mobile app.

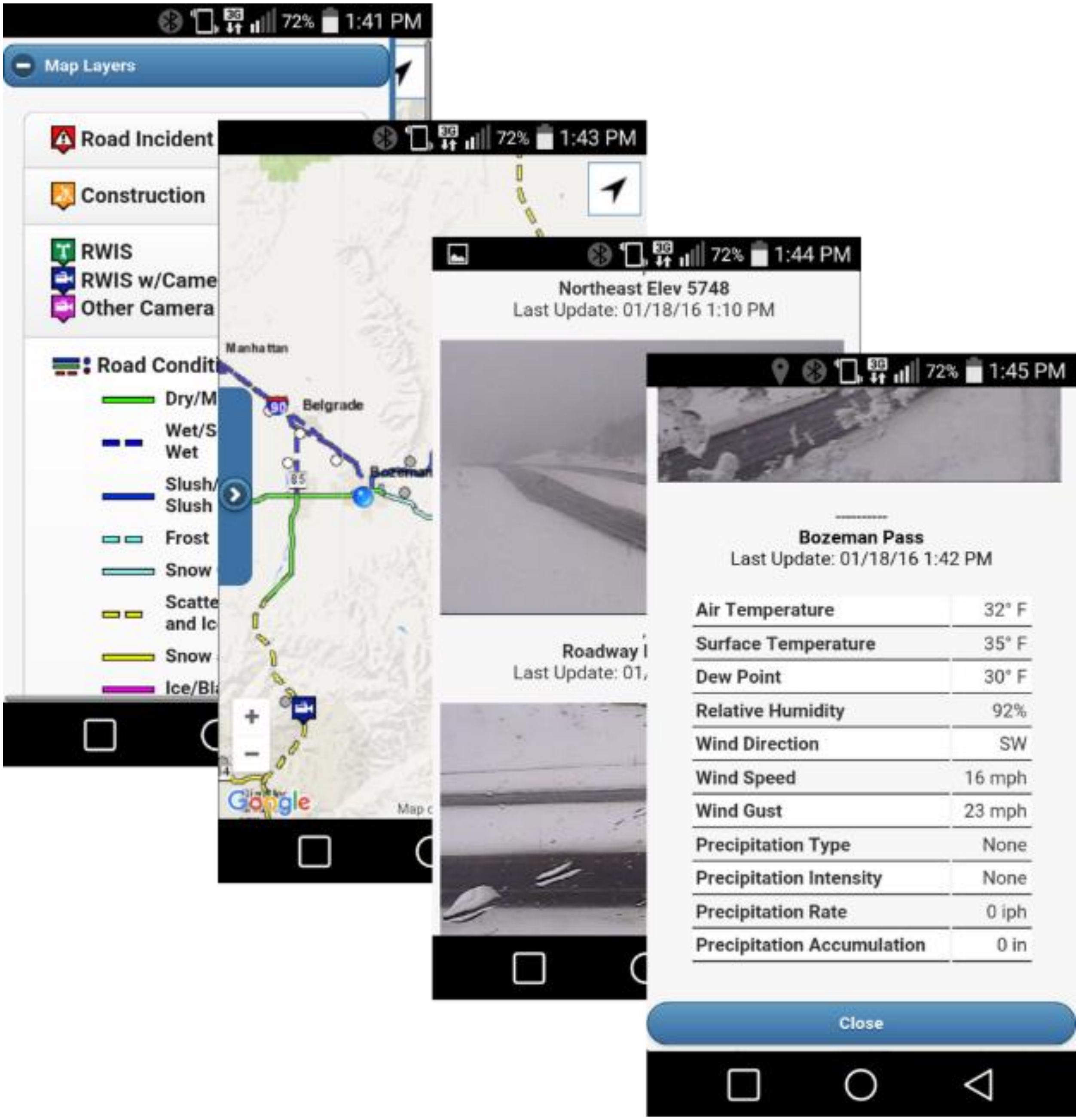


Figure 40: MDT Travel Info Mobile App

5.5. Potential Gaps: Stated Needs versus the Current System

MDT agency needs related to the RWIS program are documented in the previous *Needs Assessment* project task. Interviews and surveys of various agency stakeholders were performed and the findings documented how RWIS data are used by the agency and the needs associated with using RWIS information. Comparing the current RWIS configuration to the previously documented agency needs reveals some areas that may have opportunities for improvement.

5.5.1. Sensor / Hardware Capabilities

The current basic sensor array that exists at virtually all ESS meets most of the needs of the agency but a few sensors and weather attributes not currently available in the core ESS configuration were desired by large portions of agency users including:

- sensors that provide precipitation type and intensity or rate (currently available at 8% of sites),
- sensors that provide visibility (currently available at 5% of sites), and
- infrared lights to make camera images visible at night (currently available at 8% of sites).

5.5.2. Software Functionality

The current software does meet basic needs of the agency, but lacks certain functionalities that were desired by RWIS data users including:

- customizable alarms to alert users when certain weather conditions exist (not currently available),
- a self-diagnosis type function to discover unresponsive or malfunctioning sensors or sites (not currently available),
- mobile-device based information (currently available via travel information app only), and
- forecast information (currently available from outside sources on separate software -- NOAA or other 3rd parties).

5.5.3. Practices

Certain needs related to specific RWIS practices were also raised during the agency needs assessment including:

- polling data and images every 15 minutes (currently every 30 minutes), and
- including a horizon view for aviation users (only feasible where pan-tilt-zoom, PTZ, cameras exist, so as to not compromise the road views, PTZ cameras currently available at 45% of sites).

5.6. Alternatives

Various hardware, sensor, and software alternatives for providing RWIS data and images have been identified and those most relevant to MDT's needs are included in the following sections.

5.6.1. Sensors and Hardware

A number of alternative sensor types have been identified that may provide the additional capabilities raised from the agency needs assessment. Precipitation sensors are available with capabilities beyond yes/no occurrence readings including precipitation type, intensity, rate, and depth. These more detailed precipitation capabilities are available from a number of sensor types including atmospheric combination sensors, advanced precipitation sensors, and non-invasive pavement sensors. Figure 41 shows examples of these alternative sensor types.

Figure 41: Alternative Sensors Examples (atmospheric combination: left, advanced precipitation: center, non-invasive: right)

Visibility monitoring can be obtained from certain advanced precipitation sensors or standalone visibility sensors. Nighttime camera images may be best obtained using infrared light emitters to illuminate the camera's view of the roadway. Table 5 shows the functionality of the alternative sensor types compared to each other and the existing base ESS configuration.

Table 5: Sensors and Associated Weather Attributes

	Sensor	Air Temp., Hmd., Dew Pt.	Wind Speed & Direction	Pavement Temp.	Pavement Condition	Subsurface Temp.	Camera Image	Precip. Occurrence	Night Camera Image	Precipitation Type	Precip. Intensity or Rate	Precipitation Depth	Visibility	Road Friction
Current Base ESS Config.	Air Temp. / Humidity Sensor	X												
	Wind Speed & Direction Sensor		X											
	In-Pavement Sensor			X	X									
	Subsurface Sensor					X								
	Static Camera						X							
	Precipitation Sensor (yes/no)							X						
Alternative Sensors	Atmospheric Comb. Sensor	X	X					X		X	X	X		
	Infrared Light for Camera								X					
	Visibility Sensor												X	
	Advanced Precipitation Sensor							X		X	X		X	
	Non-Invasive Sensor	X		X	X			X		X	X	X		X

Certain older RPUs may not comply with the National Transportation Communications for ITS Protocol (NTCIP) 1204 - ESS Interface Standard. This standard is the non-proprietary communications protocol developed by a joint effort of the National Electronics Manufacturers Association (NEMA), the American Association of State Highway and Transportation Officials (AASHTO), and the Institute of Transportation Engineers (ITE) with funding from the US Department of Transportation (USDOT) Intelligent Transportation Systems Joint Program Office (ITS-JPO). NTCIP 1204 version 3 is the most recent published edition with version 4 revision underway.

All commercially available RPUs discovered for use with RWIS in this analysis are now NTCIP complaint which allows for non-proprietary polling of the data from the ESS. All RPUs currently in use at MDT RWIS sites are NTCIP compliant.

Often times RPUs can communicate successfully with sensors regardless of manufacturer, but certain sensors, especially more advanced or specialized sensors, may only communicate with same provider RPUs using proprietary communication protocols. Examples of this may include:

- RPU from provider X able to determine all in-pavement sensor readings from provider Y in full detail except precipitation depth or chemical concentration which are reduced to tiered (low, medium, high) output.
- Non-invasive sensor from provider X only able to communicate with RPUs from provider X, while non-invasive sensor from provider Y uses an open-architecture communication protocol available to any RPU provider.
- Mobile RWIS sensor from provider X only able to communicate with RPUs from provider X.

5.6.2. Software

A number of RWIS software products may be considered as potential alternatives to the current system that would be capable of meeting MDT's current needs and possibly allowing greater functionality and flexibility for the future of RWIS in Montana. There are different levels of sophistication in terms of the functionality of the RWIS software options identified from more basic observational-only type software to options that can incorporate alerts, forecasting, maintenance decision support, automated performance metrics, advanced traffic management system (ATMS) functionality, or mobile RWIS and automatic vehicle location (AVL) components.

The capabilities of the software in this section are derived from vendor created data sheets and direct communication with vendor representatives. Most of the providers aim to be flexible and provide software to meet a clients stated needs. The information in the following sections is meant to provide the typical functionalities of the software products as described by the vendor without accounting for the additional customization that may be available. Many of the more sophisticated software products are also modular allowing for the use of certain levels of functionality without having to obtain an entire all-inclusive package of all possible options.

5.6.2.1. Observational Software

The most straightforward RWIS software options are those that simply allow for the observation of the conditions and camera images at the ESS locations. They may also allow for some limited sensor history displays and map displays. The currently used SCAN Web 6.0 software fits into this category.

5.6.2.2. Alerting Functionality

The ability to add weather condition alerts or sensor/site malfunction alerts are other common functionalities of many RWIS software products. These alerts can be delivered to personnel via email, short message service (SMS), multimedia messaging service (MMS), automated voice message phone calls, or audible tones and visual alerts at a computer station. These alerts can help maintenance personnel by reducing their need to check RWIS conditions manually and rely instead on alerts to be provided when certain customizable weather conditions are met. Similarly, alerts can be created that would trigger when certain data checking routines identify malfunctioning or unresponsive sensors.

RTMC Pro software from Campbell Scientific is a highly customizable software option that has been used for certain city and county type RWIS installations. The product is designed such that users can create their own customizable displays and alarms, with or without additional assistance from Campbell Scientific. An RWIS type base project file (Road Aware) is available, but in general RTMC Pro is seemingly less of an off-the-shelf type RWIS solution for a large network like MDT's and more of a "Consumer in Control Technology" option that would allow an agency to build displays and alarms of their choosing. An example of an RWIS station display using RTMC Pro is shown in Figure 42.

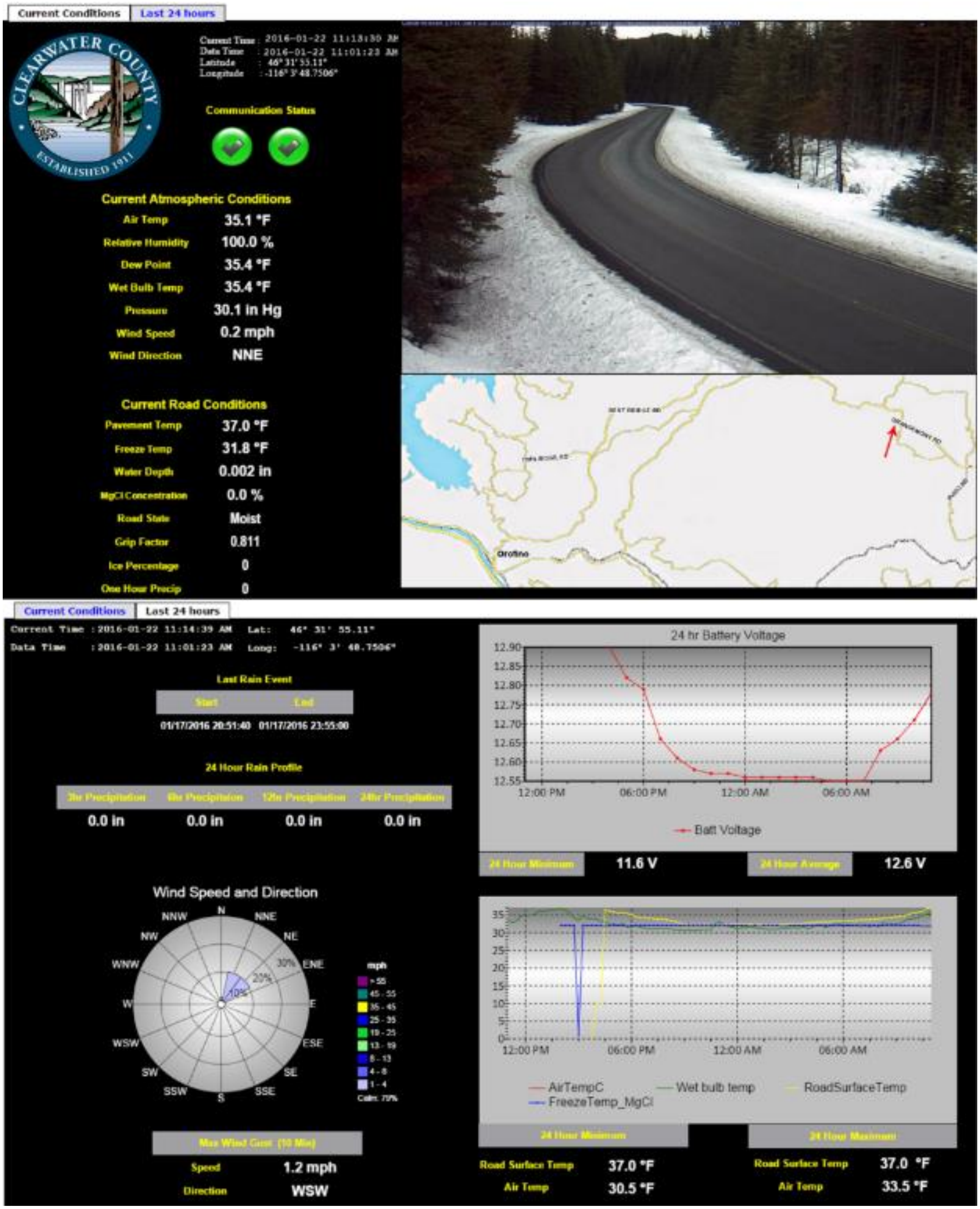


Figure 42: RTMC Pro Software Example (gc.clearwatercounty.org)

Another observational RWIS software with alerting functionality is the Geonica Suite 4K software products. No US examples of this software being used were discovered with most Geonica products being used internationally, but they are available through at least one domestic vendor (Advanced Monitoring Methods). Figure 43 shows an example of the Geonica Suite 4K software.

Figure 43: Geonica Suite 4K Software Example (english.geonica.com)

RWIS vendor High Sierra Electronics provides a couple of software products that include observational and alerting functionalities. One is known as Contrail (from OneRain Inc.) and the other is DataWise (from DataWise Environmental Monitoring, Inc.). Both of these products can provide typical map and tabular displays of current RWIS conditions and camera images along with customizable alarms. Contrail has traditionally been more focused on rainfall, flood warning, and hydrologic data monitoring, but is capable and has included RWIS sensors and cameras in a couple of locations. Contrail and DataWise are both currently used for RWIS applications at the city/county level and are not believed to be primary RWIS software for any entire state transportation agency. Figure 44 shows an example of the Contrail software being used for RWIS stations in Kansas with a map display of pavement conditions (top) and dashboard of RWIS information and cameras (bottom).

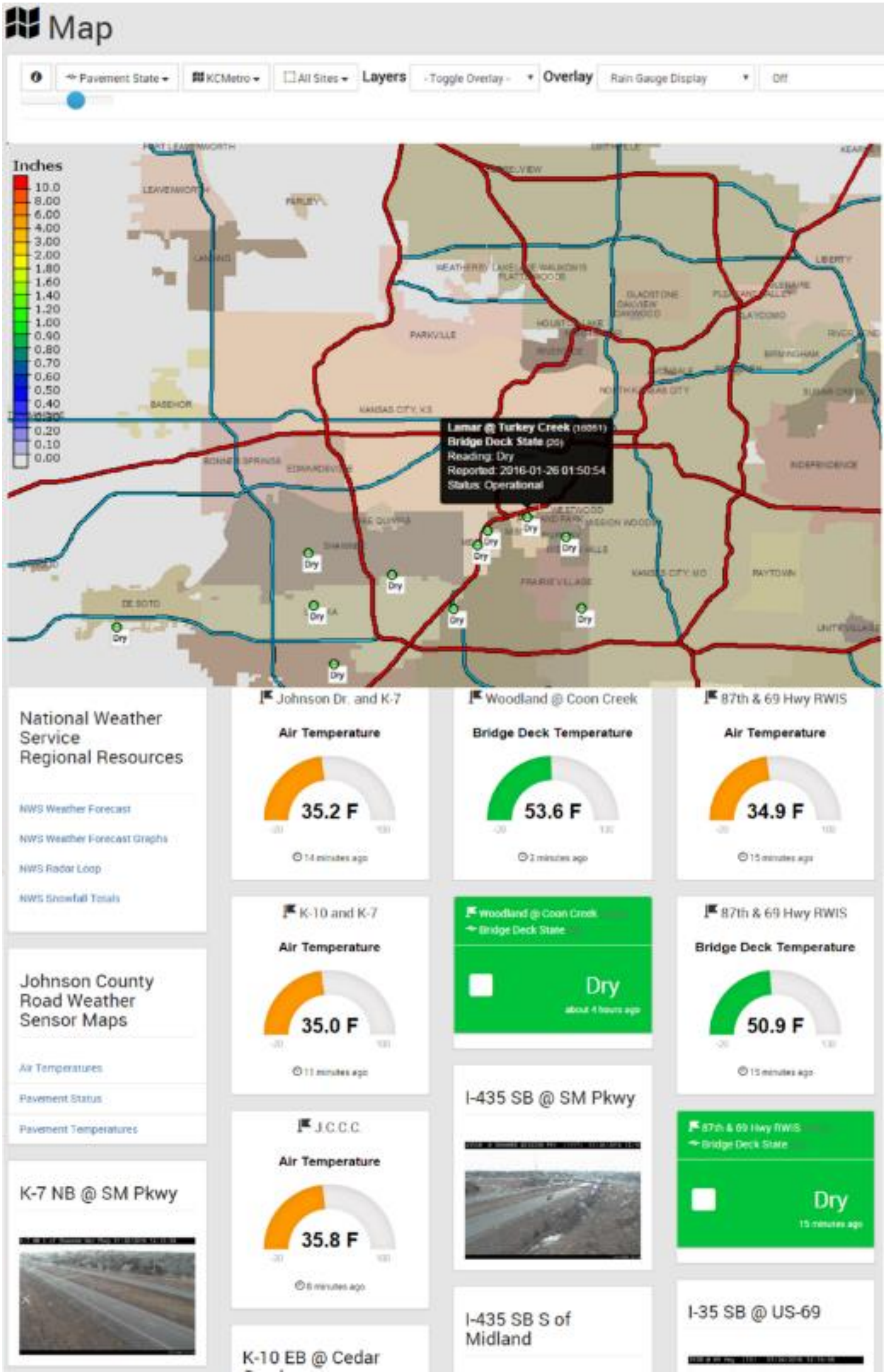


Figure 44: Contrail Software Example (contrail.opkansas.org)

Figure 45 shows an example of the DataWise software.

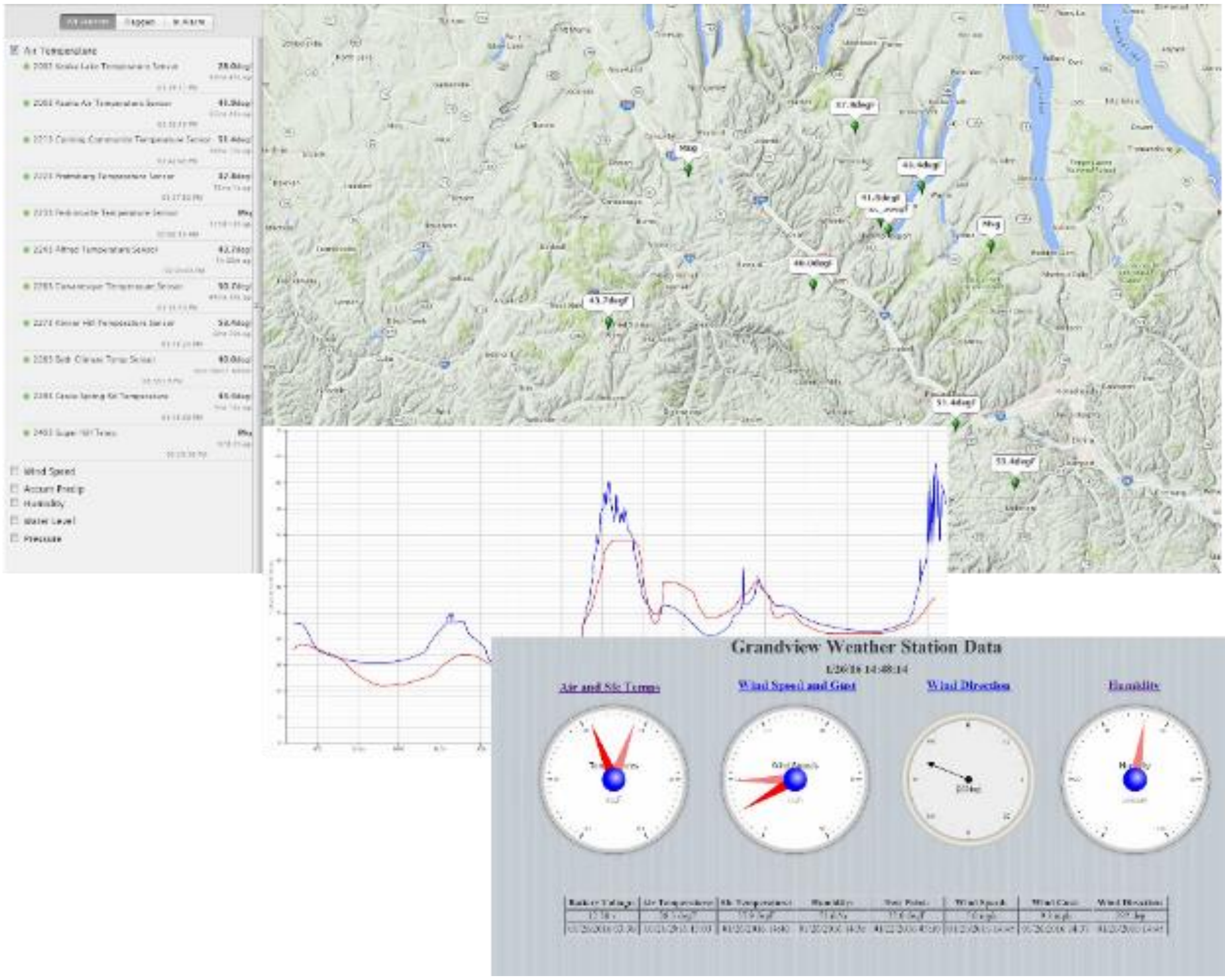


Figure 45: DataWise Software Example (courtesy of High Sierra Electronics)

RWIS provider Lufft offers a couple of software products, one of which is known as SmartView3. This software provides similar observational and alerting functionality as the others in this section. SmartView3 is used as the primary RWIS software by state transportation agencies according to the vendor. Figure 46 shows an example of the SmartView3 software.

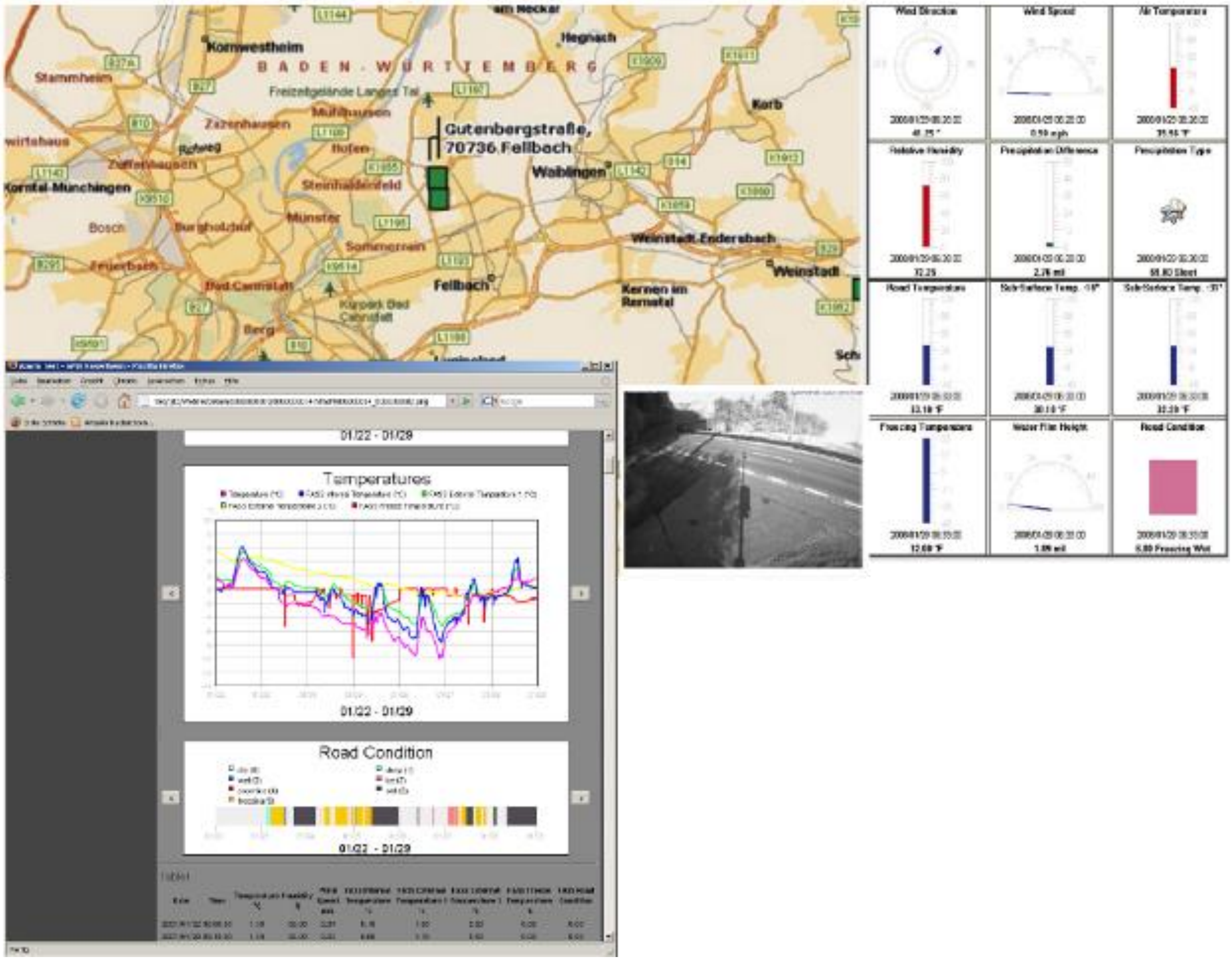


Figure 46: SmartView3 Software Example (courtesy of Lufft)

Vaisala also has a couple of software products that would be capable of supporting a state transportation agency's RWIS network. The lighter version, known as RoadDSS Observer, also fits into this observational and alerting category. Figure 47 shows an example of the RoadDSS Observer software which is also reported as being used by multiple state transportation agencies.

Figure 47: RoadDSS Observer Software Example (vaisala.com)

5.6.2.3. Forecasting and MDSS

Atmospheric weather and pavement condition forecasting can be integrated into RWIS software and provided by the primary software producer or third party sources. Often these forecasts can help determine winter maintenance actions via MDSS type suggestions that can be automated by the software. Multiple software products seem to focus on providing sophisticated atmospheric and pavement condition forecasts along with automated MDSS information. Software from Boschung, Iteris, Schneider Electric, and Vaisala all seem to provide these forecasting and decision support type information.

ClearPath Weather from Iteris is a product that seems focused on providing detailed forecasts and maintenance suggestions, but can also provide the more typical observational RWIS functionality and weather alerting. The detailed forecast information can be done independent of RWIS data inputs (which are used if available to adjust the forecasts). ClearPath Weather software is used by multiple state transportation agencies according to the vendor. Figure 48 shows a sample of some of the functionality of the ClearPath Weather software with a map and camera view (top) and a table of forecast weather and pavement conditions and MDSS actions (bottom).

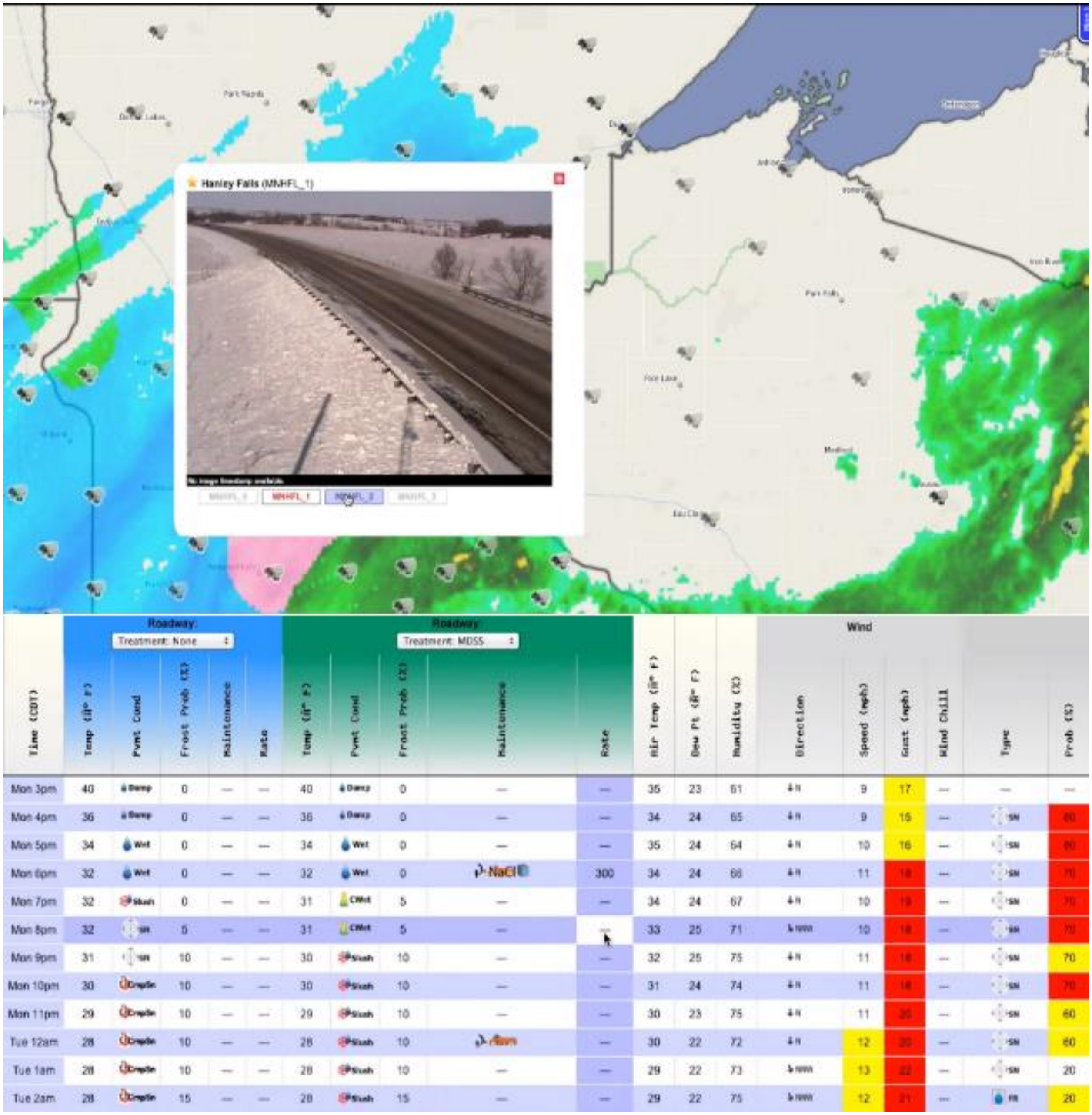


Figure 48: ClearPath Weather Software Example (clearpathweather.com)

Another robust RWIS software that can provide forecasting and maintenance decision support functions is WeatherSentry (and associated products) from Schneider Electric. This software is able to provide all the observational and alerting functions in addition to forecasting and MDSS type information. A mobile application is also available for viewing the information and forecasts on mobile devices. WeatherSentry is currently used as the primary RWIS software by multiple state transportation agencies and by the Department of Transportation in Alberta, Canada. Figure 49 shows samples of some of the functionality of the WeatherSentry software with RWIS information, pavement forecasts and MDSS treatment recommendations (top), and the mobile application (bottom).

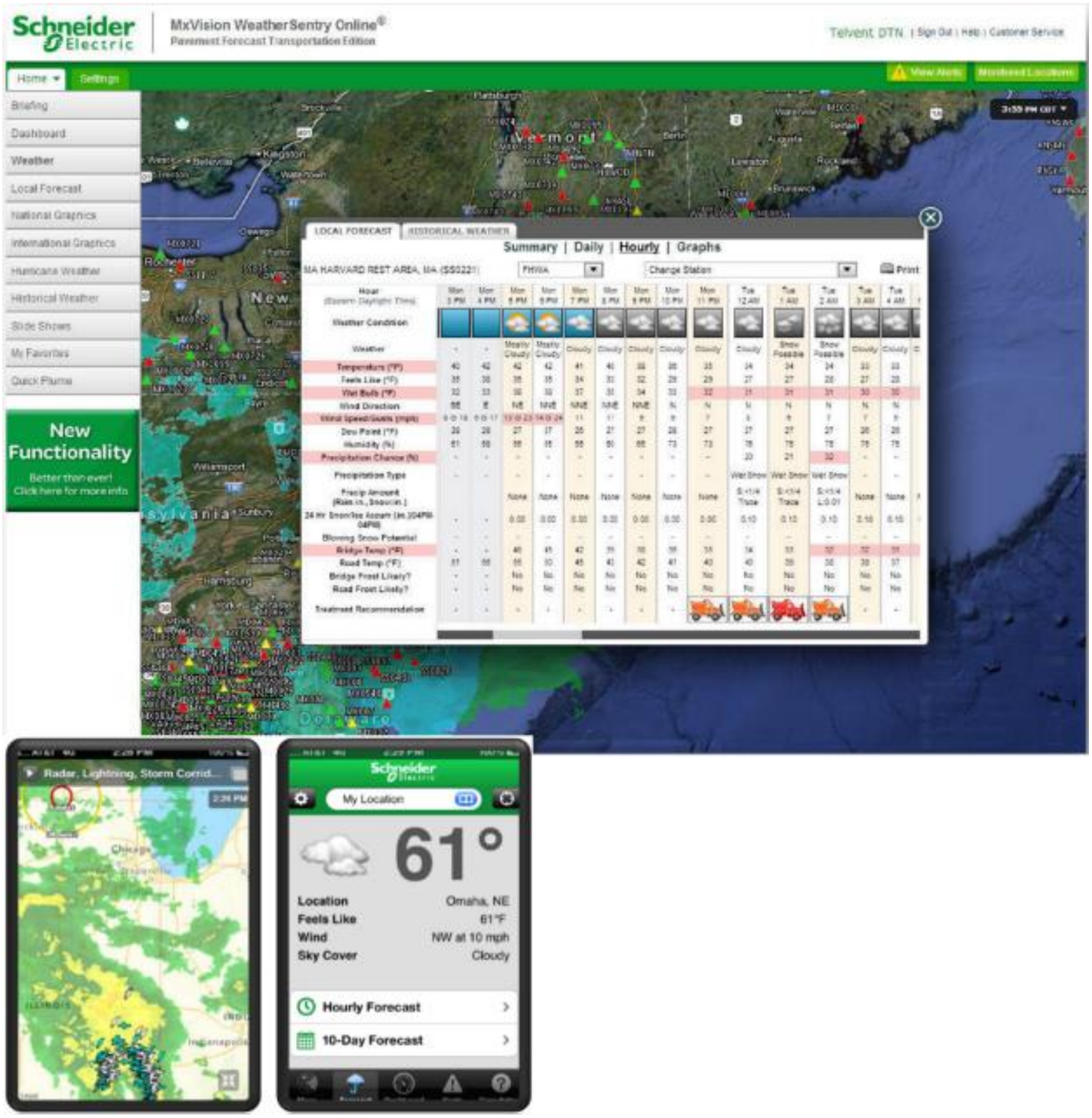


Figure 49: WeatherSentry Software Example (courtesy of Schneider Electric)

5.6.2.4. AVL and Mobile RWIS

Certain software products also integrate AVL data into RWIS software including winter maintenance type data on snowplow position and material spreader controller data in order to track maintenance vehicle locations and treatments. Mobile RWIS sensors for monitoring conditions like air temperature, pavement temperature, and surface conditions can also be integrated into certain software products. AVL and related maintenance treatment data is available with Boschung

(BORRMA-web) and Iteris (ClearPath Weather) products. Mobile RWIS sensor integration is available with Lufft (ViewMondo) and Vaisala (RoadDSS Navigator) software.

BORRMA-web from Boschung is a software option that provides AVL information in addition to forecasting and the basic observational and alarm functionality. This software is modular allowing for selection of certain functions. Boschung also offers a mobile app for observing RWIS information on mobile devices. BORRMA-web software also allows for integration with fixed automated spray technology (FAST) systems like those used to spray deicer on bridges based on ESS observations. Montana DOT now has part of the BORRMA-web software for a FAST system recently installed in Helena. The BORRMA-web software is used throughout the US on systems with a moderate number of stations, but is not believed to currently be the primary RWIS software for any entire state transportation agency. BORRMA-web is however used for larger systems internationally like for the transportation agency in Austria with hundreds of ESS locations and hundreds more AVL sensors. Figure 50 shows examples of the Boschung software with a map view and AVL data (top), forecasts (bottom, left) and the mobile app (bottom, right).

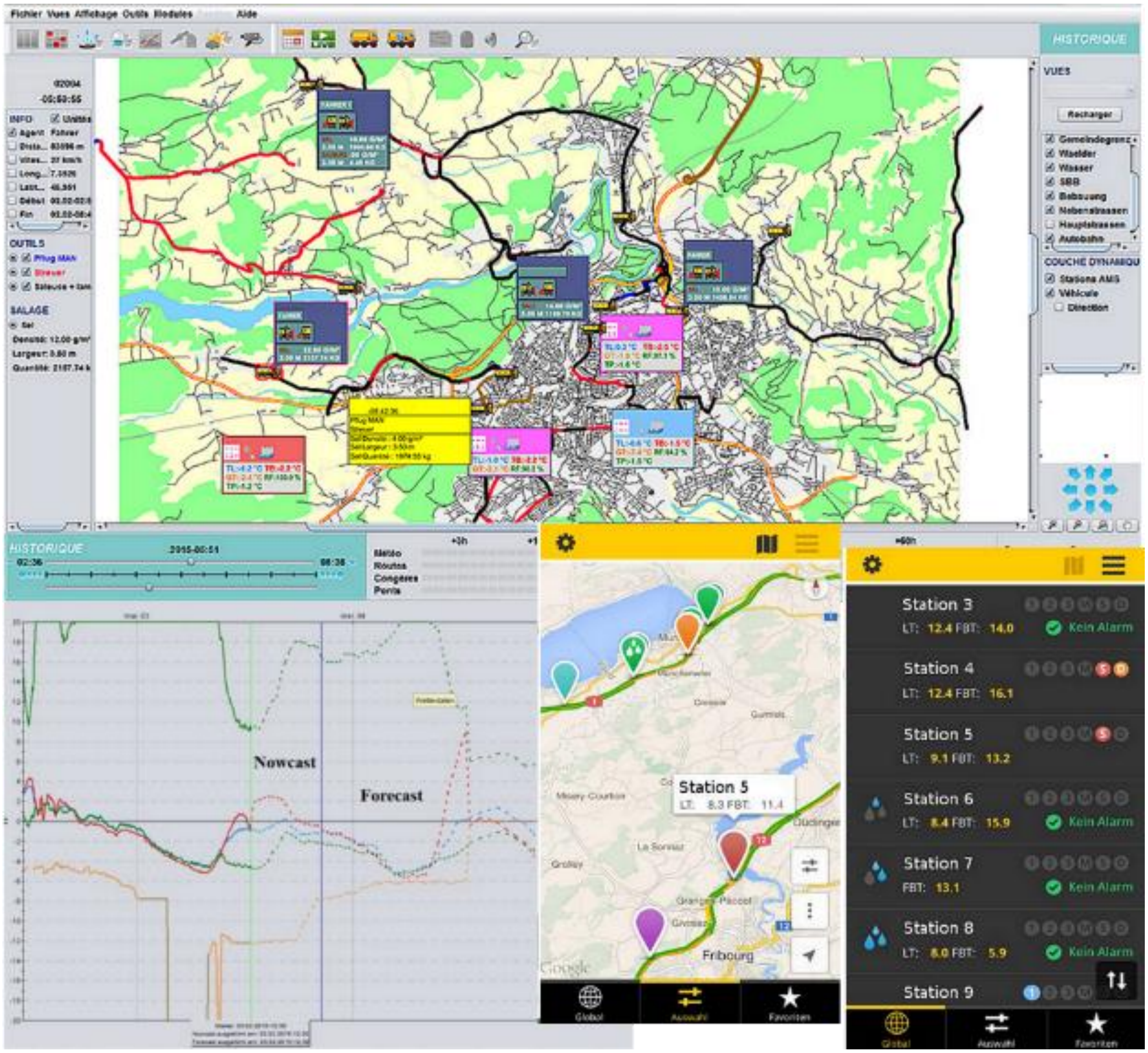


Figure 50: Boschung Software Example (boschungamerica.com & boschung.com)

Mobile RWIS sensor integration into RWIS software is available from a recently developed product known as ViewMondo (by Informatik Werkstatt in Germany). This software was developed in cooperation with RWIS provider Lufft. ViewMondo is capable of observational and alerting functions similar to Lufft's original RWIS software (SmartView3), but can also integrate with Lufft's mobile RWIS sensors. ViewMondo is not believed to be the primary RWIS software of any US state transportation agency at this time. Figure 51 shows an example of mobile sensor monitoring on ViewMondo.

Figure 51: ViewMondo Example (blog.lufft.com)

5.6.2.5. Automated Performance Measures

Vaisala's RoadDSS Navigator provides observational, alerting, forecasting, MDSS, and mobile RWIS integration functionalities along with some automated winter performance measures data which seems to be a unique functionality. RoadDSS Navigator also has a mobile app (Apple only). The winter performance measures rely on data collected from Vaisala non-invasive road weather sensors that are capable of producing a road surface friction estimate among other readings. These automated winter performance measures were recently developed in cooperation with Idaho Transportation Department (ITD) (Koeberlein, 2014). RoadDSS Navigator can quickly produce storm severity index values and winter performance measure index values which give ITD personnel some indication of the effectiveness of their winter maintenance treatments. Figure 52 shows some of the winter performance measures type information generated by the ITD RoadDSS Navigator software.

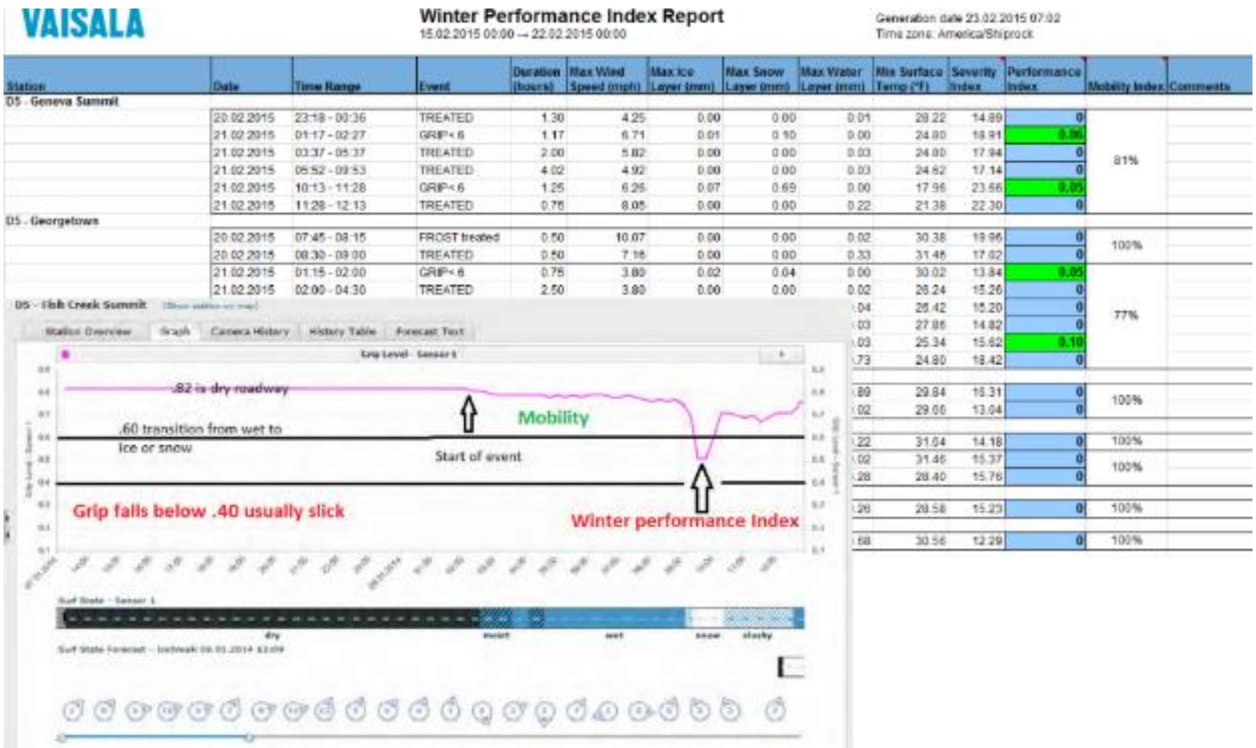


Figure 52: RoadDSS Navigator Winter Performance Measures Example

5.6.2.6. ATMS

Another software option for monitoring RWIS conditions is to utilize an ATMS software that would be capable of monitoring and controlling not just RWIS and cameras, but other agency ITS applications like DMS, highway advisory radios (HAR), traffic signals, weigh-in-motion sensors, and traveler information systems.

One example of an ATMS software that has been used as the primary RWIS software for state transportation agencies is the Intelligent NETworks ATMS software from Delcan (Parsons). This software is modular allowing agencies to choose which modules they need without having to use all 26 modules. Like the recently released MDT snow plow camera pilot project, this ATMS software can also be used to review snow plow camera images using a slider bar to quickly scroll through the images moving temporally. North Dakota is one example of a state transportation agency that has recently started utilizing Delcan ATMS software with certain modules for its RWIS needs. Figure 53 shows an example of the Intelligent NETworks ATMS software.

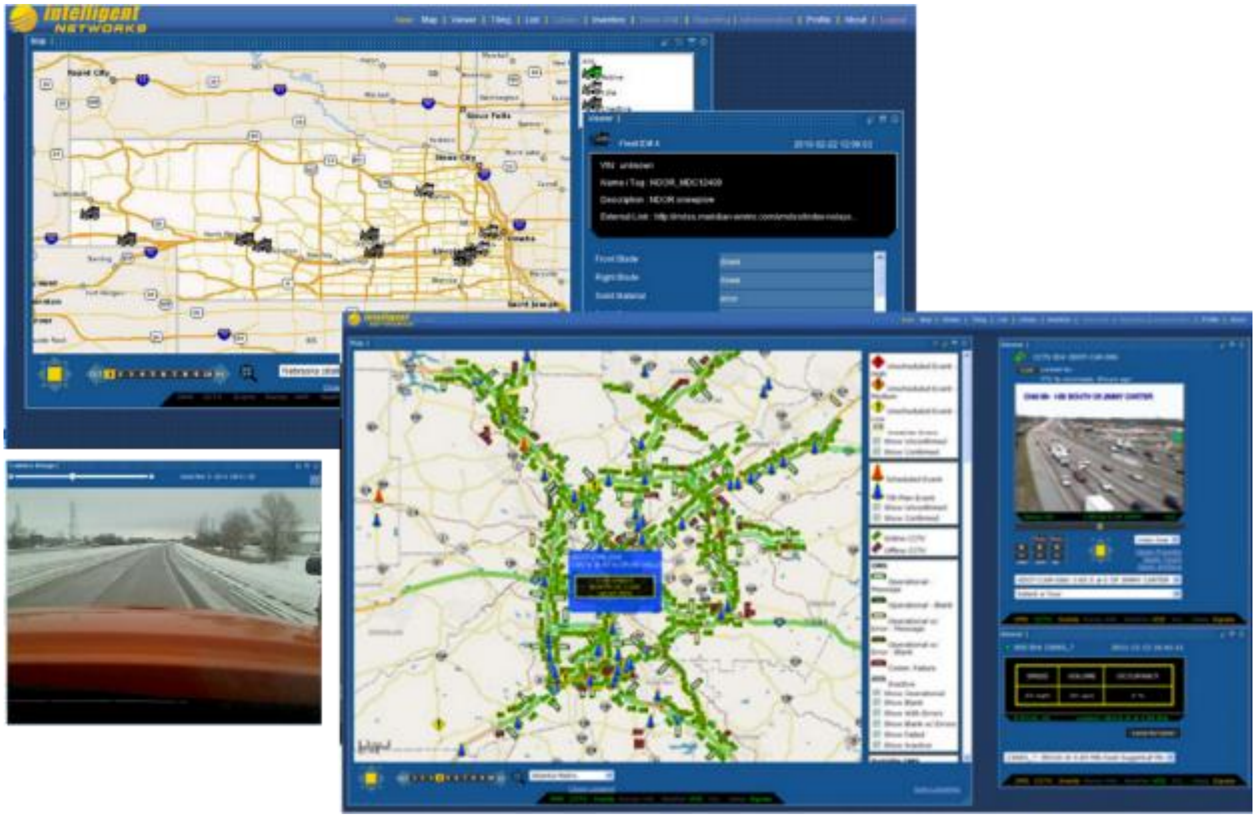


Figure 53: Intelligent NETworks ATMS Example (delcantechnologies.com)

5.6.2.7. Hosting

Many of the more sophisticated RWIS software products (and associated services) discovered in this analysis are only offered as hosted services. These hosted products do not require any physical DOT server space and the services are accessed by the agency using an internet browser. Some of the RWIS software options found during this analysis are software that is purchased and run entirely on DOT servers, and some can be either hosted or operated in-house by the DOT. Table 6 presents an overview of functionality of all of the capable RWIS software options found during this analysis including their hosting options.

Readers should note that software from Aanderaa (Xylem), All Weather Inc., and Narwhal Group may also exist, but not enough information could be found to include any of those options that may or may not be classified as alternatives suitable for MDT needs.

Table 6: Software Products and Functionality

	Observational					Alerts		Forecast			Other Functions				Hosting
	Current Data	Current Images	Data History	Map Display	Mobile App	Condition Alerts	Site Failure	Atmospheric	Pavement	MDSS	AVL	Mobile RWIS	Perf. Measures	ATMS	DOT or Hosted
SCAN Web 6.0 (Current)	●	●	●	●											DOT
MDT Travel Info Mobile App	●	●		●	●										DOT
Contrail	●	●	●	●		●	●								Either
DataWise	●	●	●	●		●	●								Either
Geonica Suite 4K	●	●	●	●		●	●								DOT
RoadDSS Observer	●	●	●	●		●	●								Hosted
RTMC Pro	●	●	●	●		●	●								DOT
SmartView3	●	●	●	●		●	●								DOT
ViewMondo	●	●	●	●		●	●					●			Hosted
WeatherSentry	●	●	●	●	●	●	●	●	●	●					Hosted
BORRMA-web	●	●	●	●	●	●	●	●	●	●	●				Either
ClearPath Weather	●	●	●	●		●		●	●	●	●				Hosted
RoadDSS Navigator	●	●	●	●	●	●	●	●	●	●		●	●		Hosted
Intelligent NETworks	●	●	●	●							●			●	DOT

Note: while a mobile app may be more robust, most options have data and images that are also viewable on mobile devices using internet browsers

5.7. Summary and Recommendations

The current RWIS program has been compared to the stated needs of the agency and the possible alternative sensor, hardware, and software options have been established. While the current system proves to be a great tool for many end users, there may be certain areas with room for improvement. Many sensor, hardware, and software alternatives have been analyzed to understand the functional opportunities they may provide. There are certain quantifiable and intangible benefits associated with some of these alternative sensor capabilities and RWIS software functionalities like forecasting, MDSS, and winter performance measures (Ye, et al. 2009; Koeberlein, et. al. 2015; Koeberlein, 2015).

Many different sensor and software alternative combinations exist. Table 7 provides a framework to visualize many of these alternatives that may be possible using different sensors and software and possible ESS expansion scenarios.

Table 7: Possible Alternatives for Benefit Cost Analysis

		Software Functionalities						
	Sensors	Obs.	Obs. + Alert	Obs. + Fcast/ MDSS	Obs. + AVL	Obs. + Mobile RWIS	Obs. + Perf. Meas.	Obs. + ATMS
Current ESS	Base	Current		A				
Current ESS	Base + IR							
Current ESS	Base + Prec. ± IR		B					
Current ESS	Base + NI ± IR						C	
ESS Expansion	Cam ± Pv. Temp	D						
ESS Expansion	Mobile RWIS					E		
ESS Expansion	Base							
ESS Expansion	Base + IR							
ESS Expansion	Base + Prec. ± IR							
ESS Expansion	Base + NI ± IR							

Note: Obs. = observational, Base = current typical base sensor configuration, IR = infrared light, Prec. = more than yes/no precipitation sensor, NI = non-invasive sensor, Cam = camera

For illustration purposes, the current scenario is shown along with some possible alternatives (A through E) that may be particularly attractive based on the needs assessment findings and prior benefit-cost literature. These possible scenarios can be described as:

- A: Use the current RWIS configuration and sites in conjunction with a software product with forecasting and MDSS type functions that may be capable of providing targeted suggestions that could save agency labor and materials.

- B: Equip the current sites with sensors to allow for more advanced precipitation monitoring (with or without night-time camera images) to meet a stated desire(s) of many maintenance users.
- C: Equip existing sites with non-invasive pavement sensors that would be required to realize the benefits of software that can produce automated winter performance measures which may in turn result in improved operations, mobility, and safety.
- D: Expand the current RWIS network using the “limited ESS” type model which may include only a camera (with or without pavement temperature sensors) to meet the stated desires from multiple user groups.
- E: Expand the current network using mobile RWIS sensors and a capable software.

These alternative possibilities were used in consultation with the MDT Technical Panel to establish which alternatives to include in the benefit cost analysis (see Chapter 6).

6) BENEFIT-COST ANALYSIS

This chapter details the benefit cost analysis which determines the economic outcomes of different RWIS alternatives. The alternatives defined in Chapter 5 were reviewed in consultation with the MDT project Technical Panel to ensure the most pertinent alternatives and approaches were included in this analysis.

The analysis includes the identified software functionalities in addition to different expansion scenarios. Specifically, alerting functionality, winter maintenance performance measures, and forecasting/MDSS functionalities were requested for investigation. Also requested was an analysis of different RWIS expansion alternatives (i.e. fixed stations compared to mobile RWIS, non-invasive sensors compared to in-pavement sensors). Table 8 shows the analysis alternatives, given that the expansion methods and software functionalities are not independent of one another.

Table 8: Analysis Alternatives

Coverage	Software Functionalities			
	Observational	Observational + Alerting	Observational + Forecast/MDSS	Observational + Perf. Measures
Current	Baseline	1	2	3 *
Current + Base Expansion	A	1 A	2 A	3 A *
Current + Simple Expansion	B	1 B	2 B	3 B *
Current + Non-Inv. Expansion	C	1 C	2 C	3 C *
Current + Mobile Expansion	D	1 D	2 D	3 D *

* Would require current coverage be supplemented with non-invasive sensors.
Note: Base expansion includes new ESS that are configured similarly to current base configuration.
Note: Simple expansion includes new ESS that have only a camera and in-pavement sensor.

In order to address the economic feasibility of both the software functionalities as well as the expansion alternatives, seven total scenarios (1, 2, 3, A, B, C, D) were investigated in detail relative to the current baseline situation. The quantified details of these seven scenarios are then used in combination to infill the remaining 12 possibilities (1A, 2A, etc.) which are a mix of the related benefits and costs while also accounting for any synergistic savings or benefits that exist for certain combinations.

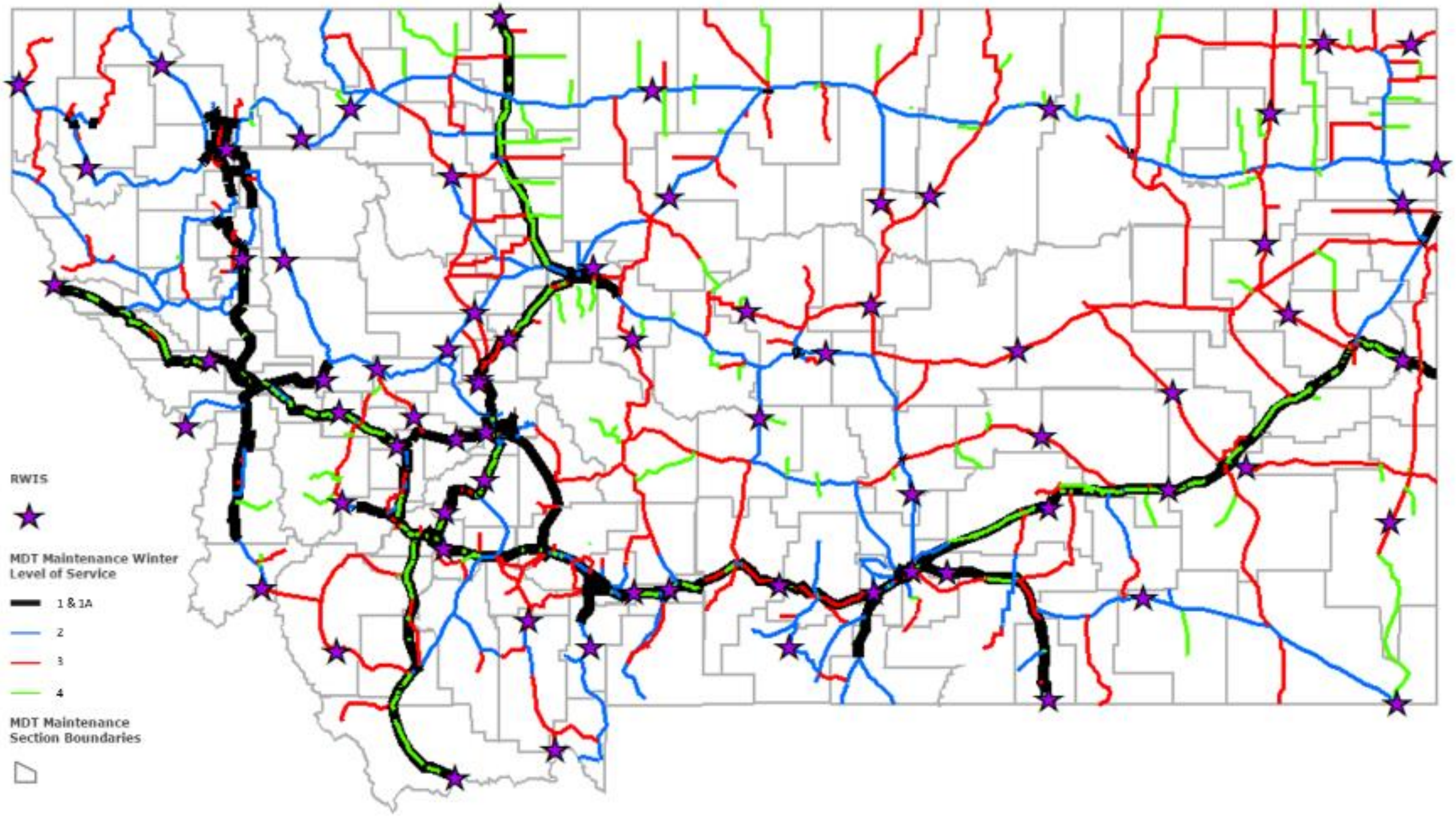
6.1. Background

The current RWIS system is used by the primary users group, MDT winter maintenance personnel, to monitor conditions and make decisions related to preventing and removing ice and snow from Montana’s roads. MDT maintenance personnel receive NWS forecasts and utilize other online, TV, and newspaper weather forecasts to be aware of upcoming winter storms. These forecasts help supervisors plan in advance of a storm in terms of how many crew members to have prepared and with what equipment and materials ready. Depending on the specifics of the storm forecast and the actual storm event, maintenance crews may utilize liquid or solid anti-icing or deicing materials, abrasives, pre-wetted abrasives, and snowplowing in various combinations. MDT practices “just-in-time” anti-icing, which is a practice that does not apply anti-icing materials until the actual start of a storm event (except for bridges and locations that receive little sunlight) in order to avoid applying anti-icing materials unnecessarily if a storm event doesn’t materialize despite being forecast.

There are currently 118 maintenance sections around the state staffed by a total of approximately 709 winter maintenance crew members. Maintenance crews in each section maintain their roads according to certain Winter Maintenance Service Level Guidelines. These guidelines define levels of service and a general prioritization of winter maintenance activities and methods to be used depending on characteristics of each route. The different levels are:

- Type I & I-A: urban routes, Interstates, and other roads with ADT greater than 3000 vpd;
- Type II: roads with ADT from 1000 to 3000 vpd;
- Type III: roads with 200-1000 vpd;
- Type IV: roads with less than 200 vpd; and
- Type V: roads that are seasonally closed and don’t receive any regular winter maintenance treatments.

Each winter maintenance service level type includes specific guidelines for the typical methods and common treatment service hours to be expected. Figure 54 shows the different service levels, maintenance sections, and RWIS sites around the state.



*map does not show 7 satellite maintenance sections that operate within certain of the 118 sections (125 sections total)

Figure 54: Maintenance Sections, RWIS sites, and Winter Maintenance Service Levels

Some maintenance sections are tasked with maintaining mostly urban and Interstate routes while other maintenance sections primarily treat type III and IV roads. In general better RWIS coverage exists for those sections that are tasked with maintaining the higher service level roads.

The level of RWIS coverage may affect certain winter maintenance crew practices. For example, a crew in a remote section with poor RWIS coverage may need to rely on more patrolling to monitor the condition of roads and the potential start of a storm event, while a crew in a more urban area with good RWIS coverage may be able to largely avoid patrols and rely on RWIS observations. These differences affect the quantification of the benefits and costs associated with some of the alternatives in this economic analysis. As a result, and to provide the best possible estimates, the level of RWIS coverage was rated for each maintenance section on a 3 tier scale:

- Good RWIS coverage was assigned to a section if the majority of its roads are within 20 miles of RWIS sites.
- Fair RWIS coverage was assigned to a section if the majority of its roads are 20 to 40 miles from RWIS sites.
- Poor RWIS coverage was assigned to a section if the majority of its roads are more than 40 miles from RWIS sites.

These 3 general RWIS coverage classes will be used for benefit and cost calculations in the following sections. Overall 69 sections (58.5%) were found to have good RWIS coverage, 44 sections (37.3%) were found to have fair RWIS coverage, and 5 sections (4.2%) were found to have poor RWIS coverage.

Another quantity that affects many of the benefit cost scenarios is the level of geographic coverage related specifically to the different expansion methods. For calculation purposes a 25% geographic coverage expansion is used throughout the analyses. In accordance with coverage ranges from the literature reviewed in a prior task, a single RWIS site is assumed to have a geographic coverage of 25 miles. Actual RWIS coverage is highly dependent on local factors and is different for more mountainous western Montana geographies which may benefit from spacing even closer than 25 miles in certain instances compared to flatter eastern Montana areas that may be adequately covered with RWIS spacing greater than 25 miles.

6.2. Benefits and Costs of Alternatives

Each alternative scenario is evaluated relative to the current baseline situation. Each scenario considers as many *documented/estimable* and *intangible/unquantified* benefits and costs as possible. In general this includes the following aspects:

Benefits

Agency

- Reduced maintenance labor or increased labor efficiency,
- Reduced maintenance material use, and
- Reduced maintenance equipment use or increased equipment efficiency

Societal

- Reduced crash occurrence and/or severity,
- Reduced travel time or reduced delays or improved level of service (LOS), and

- Better Traveler Information and related decision making

Costs

- Tower and foundation,
- Sensors and hardware,
- Communications,
- Power,
- Software,
- Vendor services (e.g. forecasts, MDSS),
- Installation,
- Training,
- RWIS hardware and communications maintenance,
- RWIS software operations & maintenance, and
- Administrative (e.g. management, protocol development)

While the best estimates available are used throughout this analysis, many individual costs and benefits have a limited amount of known data. The quantified benefits and costs are cited throughout this document to indicate their source be it existing literature, estimation, or vendor references. The values used reflect the researcher's best estimates, but readers are advised to exercise judgement in regards to the level of certainty associated with the assumptions required by the analyses. In general, benefit quantities are based on prior studies and conservative values are used. Vendor provided costs are typically rather rough estimates considering the uncertainty involved in changes to a large RWIS program. General estimates that apply to all scenarios are included in the following paragraphs with scenario specific values included in each respective scenario in the following subsections.

The net present value of the benefits and costs for all scenarios are determined using a 10 year period and a 7% discount rate with all hardware having a 10 year life cycle. A range of benefit-cost ratios are established for each scenario using the agency specific benefits and total benefits (agency + societal) in comparison to a range of costs (minimum to maximum). The most and least costly software and sensor options are shown for each scenario in the following sections. Rough cost estimates are used as provided from RWIS vendors wherever possible.

MDT owned and operated software options are assumed to have similar yearly software maintenance costs as the current situation with MDT maintaining ScanWeb6. Fully hosted software options that may require no or little MDT software maintenance are assumed to have an approximate savings of ***$10,000*** per year. The purchasing of additional servers for MDT owned and maintained software are not included, and existing MDT hardware may or may not be adequate for some or all alternatives. In general the initial cost of hardware may be minimal compared to other costs over the life of the alternatives.

All software options, except for Vaisala products are assumed to have an initial migration and commissioning cost of ***$10,000*** related to initial set-up, polling and customization that may be required for non-Vaisala software integrating with existing Vaisala RPUs. Additional sensors required in expansionary scenarios are estimated to have ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance costs (McKeever, et. al., 1998; Veneziano, et. al., 2014). Also new expansionary sensors are estimated to have ***$600*** per year power and communications costs.

The maximum benefit-cost ratio is determined using the lowest net present worth combination of software and hardware costs for each scenario noting that some more specialized sensors or functionalities may require same provider hardware-software combinations. Similarly, the minimum benefit-cost ratio is determined using the highest net present worth combination of software and hardware costs. Additional calculation details are provided in Appendix C.

6.2.1. Baseline (Observational, No Expansion)

The current baseline scenario is described in the background section and all alternatives quantify benefits and costs relative to changes from the current baseline situation.

6.2.2. Scenario 1 (Observational + Alerting, No Expansion)

This scenario includes using the current RWIS sites with a software capable of providing customizable alerts for different weather conditions as well as for unresponsive or malfunctioning sensors and sites.

Main Personnel Impacts

- Maintenance crews could rely on an alert via email, text message, or phone call for specific RWIS weather conditions as opposed to needing to check RWIS sites periodically in anticipation of required winter maintenance activities. This would likely eliminate the need to check RWIS observations in those sections with good and fair RWIS coverage.
- Alerts may also result in maintenance crews being able to optimally time activities, especially “just-in-time” anti-icing. The alerts would likely reduce the probability of starting activities later than desired by eliminating the potential for a crew member to miss or delay the checking of RWIS observations.
- Communications personnel could rely on alerts of problematic sensors and sites as opposed to being alerted by public users that may be using traveler information sources.

Benefits

Documented / Estimable:

- Reduced labor related to checking RWIS weather conditions.
    - 57.9 winter related event days per year (*documented: App. C*)
    - 11.6 maintenance sections effected per storm (*documented: App. C*)
    - 6 potentially effected personnel per section (*documented: App. C*)
    - $32 per hour average personnel rate with benefits (*provided*)
  - Sections with good RWIS coverage:
    - 10 minutes per effected crew member per storm event (*estimated*)
    - 69 sections with good RWIS coverage (*documented: Sec. 6.1*)
  - Sections with fair RWIS coverage:
    - 5 minutes per effected crew member per storm event (*estimated*)
    - 44 sections with fair RWIS coverage (*documented: Sec. 6.1*)

$$Savings = \left(\frac{10\ min}{60\ min/hr} * \frac{\$32}{crew,hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{69\ good\ sctns}{118\ total\ sctns}\right) + \left(\frac{5\ min}{60\ min/hr} * \frac{\$32}{crew,hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{44\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{16,575\ per\ yr}$$

- Reduced crash occurrence from less time with snowy/icy roads related to reduced late anti-icing, deicing and plowing.
    - 5% of storms with later-than-desired maintenance start (*estimated*)
    - $1.1665 crash cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. C*)
  - Sections with good RWIS coverage:
    - 10 minutes less untreated road time per late-start storm event (*estimated*)
    - 69 sections with good RWIS coverage (*documented: Sec. 6.1*)
  - Sections with fair RWIS coverage:
    - 5 minutes less untreated road time per late-start storm event (*estimated*)
    - 44 sections with fair RWIS coverage (*documented: Sec. 6.1*)

$$Savings = \left(5\% * \frac{10\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{69\ good\ sctns}{118\ total\ sctns}\right) + \left(5\% * \frac{5\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{44\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{38,632}\ per\ yr$$

- Reduced delay from less time with snowy/icy roads related to reduced late anti-icing, deicing and plowing.
    - 5% of storms with later-than-desired maintenance start (*estimated*)
    - $0.1469 delay cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. C*)
  - Sections with good RWIS coverage:
    - 10 minutes less untreated road time per late-start storm event (*estimated*)
    - 69 sections with good RWIS coverage (*documented: Sec. 6.1*)
  - Sections with fair RWIS coverage:
    - 5 minutes less untreated road time per late-start storm event (*estimated*)
    - 44 sections with fair RWIS coverage (*documented: Sec. 6.1*)

$$Savings = \left(5\% * \frac{10\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{69\ good\ sctns}{118\ total\ sctns}\right) + \left(5\% * \frac{5\ min}{storm} * \frac{1\ storm}{360\ min} * \frac{\$1.1665}{VMT} * \frac{30.92MVMT}{yr} * \frac{44\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{4,865}\ per\ yr$$

Intangible/Unquantified:

- Fewer reports from public of malfunctioning sites or sensors.
- Potentially less time with malfunctioning sites or sensors.

<u>Costs</u>

- Software
  - Minimum
    - Agency purchased and maintained software
      - ***$10,500*** purchase license (*vendors*)
      - ***-$0*** yearly O&M savings versus current (*see Sec. 6.2*)
      - ***$10,000*** initial migration (*see Sec. 6.2*)
  - Maximum
    - Hosted software service
      - ***$73,000*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)

<u>Benefit - Cost Ratio</u>

- Agency: ***0.3*** to ***5.7***
- Total: ***1.0*** to ***20.6***

6.2.3. Scenario 2 (Observational + Forecasting/MDSS, No Expansion)

This scenario includes using the current RWIS sites with a software and service capable of providing detailed atmospheric and pavement forecasts with some treatment recommendations type decision support based on the forecasts. Note that true "MDSS" treatment functionality is best obtained when an agency reports actual winter maintenance treatments back to the provider, which are then used to improve the forecasts and additional treatment recommendations (Ye, et. al., 2009b). The benefits of this scenario are based more on the value of improved weather forecasting information (that may or may not come with basic treatment recommendations), as opposed to full MDSS type benefits. Software options that provide forecasting and MDSS type information also typically have the alerting functionality as detailed in Scenario 1, so alerting functionality benefits are included where appropriate.

<u>Main Personnel Impacts</u>

- All impacts from Scenario 1.
- Improved atmospheric forecasting, pavement forecasting, and treatment recommendations have been shown to reduce total labor and material costs (Ye, et. al., 2009a; Strong & Shi, 2008; Shi, 2015).
- More precise forecasts with standardized treatment recommendations would likely increase the amount of proactive anti-icing performed overall. It will also likely allow for earlier treatments than the "just-in-time" anti-icing practices with more accurate and location specific forecasts resulting in fewer forecast storms that don't materialize.

Benefits

Documented / Estimable:

- Reduced labor from improved forecasting / decision support.
    - 11% (conservative) total labor cost reduction[1] (*Strong & Shi, 2008*)
    - \$17.39M yearly winter maintenance labor costs (*documented: App. C*)

$Savings = 11\% * \$17.39M = \$\mathbf{1.91M}\ per\ yr$

- Reduced material use from improved forecasting / decision support.
    - 4% (conservative) total materials cost reduction (*Strong & Shi, 2008*)
    - \$10.87M yearly winter maintenance materials costs (*documented: App. C*)
    -

$Savings = 4\% * \$10.87M = \$\mathbf{434,800}\ per\ yr$

- Reduced crash occurrence from less time with snowy/icy roads related to increased proactive anti-icing.
    - 10% more proactive anti-icing overall (*estimated*)
    - \$0.1263 crash cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. C*)

$$Savings = 10\% * \frac{\$0.1263}{VMT} * 30.92MVMT = \$\mathbf{390,520}\ per\ yr$$

- Reduced delay from less time with snowy/icy roads related to increased proactive anti-icing.
    - 10% more proactive anti-icing overall (*estimated*)
    - \$0.0294 delay cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. C*)

$$Savings = 10\% * \frac{\$0.0294}{VMT} * 30.92MVMT = \$\mathbf{90,905}\ per\ yr$$

Intangible/Unquantified:

- Ability to have consistent statewide treatment suggestion protocols based on conditions and forecasts.
- Fewer reports from public of malfunctioning sites or sensors.
- Potentially less time with malfunctioning sites or sensors.

[1] The labor savings related to alerting functionality is taken as part of the total 11% reduction and not included again.

<u>Costs</u>

- Software
    - Minimum
        - Agency purchased and vendor maintained software
            - ***$417,600*** purchase license (*vendors*)
            - ***$20,100*** yearly vendor maintenance (*vendors*)
            - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)
            - ***$10,000*** initial migration (*see Sec. 6.2*)
    - Maximum
        - Hosted software service
            - ***$146,300*** per year (*vendors*)
            - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)
            - ***$10,000*** initial migration (*see Sec. 6.2*)

<u>Benefit - Cost Ratio</u>

- Agency: ***17.1*** to ***29.8***
- Total: ***20.5*** to ***36.0***

6.2.4. Scenario 3 (Observational + Performance Measures, No Expansion)

This scenario includes using the current RWIS sites with a software and service capable of providing automated performance measures information. Automated performance measures require the use of non-invasive sensor technologies capable of estimating a grip level. This scenario will consider equipping 25% of the current sites with non-invasive sensors which will result in approximately 25% of the storm effected VMT being influenced (a conservative estimate as it is more likely non-invasive sensors would be placed at winter maintenance service level I and IA routes that serve higher traffic levels). Software that provides automated performance measures also provides alerting functionality, so those impacts are included where appropriate. The software that provides automated performance measures also has an option to provide forecasting and MDSS type information. Benefit-cost ratios are therefore provided with and without the advanced forecasting/MDSS options.

<u>Main Personnel Impacts</u>

- All impacts from Scenarios 1[2] and 2.
- The use of automated performance measures is only known to have been implemented in one state transportation agency (Idaho). That agency has reported improvements in overall winter road conditions related to their ability to adjust winter maintenance activities based on monitoring the grip levels of the roadway (Koeberlein, et. al., 2015; Koeberlein, 2015).

[2] In the case of not having forecasts, labor saving from alerting functionality is included.

<u>Benefits</u>

Documented / Estimable:

- Reduced material use from grip monitoring and material use optimization.
  - Only for sections with non-invasive sensor coverage:
    - 25% of total VMT with non-invasive coverage (*assumed above*)
    - 20% (conservative) total materials cost reduction (*documented: App. C*)
    - $10.87M yearly winter maintenance materials costs (*documented: App. C*)

$$Savings = 25\% * 20\% * \$10.87M = \$\mathbf{543,500}\ per\ yr$$

- Reduced crash occurrence from less time with lower grip levels.
  - Only for sections with non-invasive sensor coverage:
    - 25% of total VMT with non-invasive coverage (*assumed above*)
    - $0.2101 crash cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. C*)

$$Savings = 25\% * \frac{\$0.2101}{VMT} * 30.92MVMT = \$\mathbf{1.62M}\ per\ yr$$ [3]

- Reduced delay from less time with lower grip levels.
  - Only for sections with non-invasive sensor coverage:
    - 25% of total VMT with non-invasive coverage (*assumed above*)
    - $0.0499 crash cost savings per treated VMT (*documented: App. C*)
    - 30.92 MVMT storm effected traffic (*documented: App. C*)

$$Savings = 25\% * \frac{\$0.0499}{VMT} * 30.92MVMT = \$\mathbf{385,727}\ per\ yr$$

Intangible/Unquantified:

- Ability to monitor and report winter maintenance performance measures in terms of improved mobility and safety provided to the travelling public.
- Ability to have consistent statewide treatment suggestion protocols based on conditions and forecasts if advanced forecasting is used.
- Fewer reports from public of malfunctioning sites or sensors.
- Potentially less time with malfunctioning sites or sensors.

[3] Conservative compared to crash reductions observed with similar sensor numbers in Idaho (Koeberlein, et. al., 2015).

Costs

- Software
    - One option
        - Hosted software service (without forecasting)
            - ***$76,650*** per year (*vendors*)
            - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)
        - Hosted software service (with forecasting)
            - ***$89,800*** per year (*vendors*)
            - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)
- Hardware
    - Noninvasive Sensors (matching single option software)
        - ***$20,000*** each (*vendors*)

Benefit - Cost Ratio

- Agency (without forecasting): ***~4.8***
- Total (without forecasting): ***~21.8***

- Agency (with forecasting): ***~17.9***
- Total (with forecasting): ***~33.3***

6.2.5. Scenario A (Observational, Base Expansion)

This scenario includes using the current observational software with the current RWIS sites and 18 additional "base" RWIS sites which are configured to include the same equipment as the majority of the current sites.

Main Personnel Impacts

- Maintenance crews in expansion areas that currently have poor or fair RWIS coverage would likely be improved to good RWIS coverage and could then reduce patrolling by relying on RWIS observations.

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols.
    - 57.9 winter related event days per year (*documented: App. C*)
    - 11.6 maintenance sections effected per storm (*documented: App. C*)
    - 6 potentially effected personnel per section (*documented: App. C*)
    - $32 per hour average personnel rate with benefits (*provided*)
    - $30 per hour patrol vehicle cost (*estimated*)

- Sections with previously poor RWIS coverage:
  - 30 minutes per effected crew member per storm event (*estimated*)
  - 5 improved coverage sections (*documented: Sec. 6.1*)
- Sections with previously fair RWIS coverage:
  - 15 minutes per effected crew member per storm event (*estimated*)
  - 13 improved coverage sections (*documented: Sec. 6.1*)

$$Savings = \left(\frac{30\ min}{60\ min/hr} * \frac{\$62}{crew{,}hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{5\ sctns}{118\ total\ sctns}\right) + \left(\frac{15\ min}{60\ min/hr} * \frac{\$62}{crew{,}hr} * \frac{57.9\ stm}{yr} * \frac{11.6\ eff.sctns}{storm} * \frac{6\ crew}{eff.sctn} * \frac{13\ fair\ sctns}{118\ total\ sctns}\right) = \$\mathbf{12{,}175}\ \boldsymbol{per\ yr}$$

- Reduced crash occurrence from improved conditions due to RWIS presence improvements.
  - 30.92 MVMT storm effected traffic (*documented: App. C*)
  - Sections with previously poor RWIS coverage:
    - $0.0618 crash cost savings per treated VMT (*documented: App. C*)
    - 5 improved coverage sections (*documented: Sec. 6.1*)
  - Sections with previously fair RWIS coverage:
    - $0.0309 crash cost savings per treated VMT (*documented: App. C*)
    - 13 improved coverage sections (*documented: Sec. 6.1*)

$$Savings = \left(\frac{5\ sctns}{118\ total\ sctns} * \frac{\$0.0618}{VMT} * 30.92MVMT\right) + \left(\frac{13\ sctns}{118\ total\ sctns} * \frac{\$0.0309}{VMT} * 30.92MVMT\right) = \$\mathbf{186{,}227}\ per\ yr$$

- Reduced delay from improved conditions due to RWIS presence.
  - 30.92 MVMT storm effected traffic (*documented: App. C*)
  - Sections with previously poor RWIS coverage:
    - $0.0147 crash cost savings per treated VMT (*documented: App. C*)
    - 5 improved coverage sections (*documented: Sec. 6.1*)
  - Sections with previously fair RWIS coverage:
    - $0.00735 crash cost savings per treated VMT (*documented: App. C*)
    - 13 improved coverage sections (*documented: Sec. 6.1*)

$$Savings = \left(\frac{5\ sctns}{118\ total\ sctns} * \frac{\$0.0147}{VMT} * 30.92MVMT\right) + \left(\frac{13\ sctns}{118\ total\ sctns} * \frac{\$0.00735}{VMT} * 30.92MVMT\right) = \$\mathbf{44{,}297}\ per\ yr$$

Intangible/Unquantified:

- Improved Traveler Information in areas that may have had no information.
- Improved information, especially camera images, for MDT Aeronautics and general aviation.

- Certain in-pavement sensors can output a friction estimate allowing for the possibility to store and review basic mobile sensor grip level information.

Costs

- Hardware
    - ***$35,000*** to ***$45,000*** per new base site (*estimate*)
    - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 6.2*)
    - ***$600*** yearly power and communications costs per site (*see Sec. 6.2*)

Benefit - Cost Ratio

- Agency: ***0.06*** to ***0.09***
- Total: ***1.2*** to ***1.8***

6.2.6. Scenario B (Observational, Simple Expansion)

This scenario includes using the current observational software with the current RWIS sites and 18 additional "simple" RWIS sites which are configured to include only a camera and pavement temperature sensor.

Main Personnel Impacts

- Same as Scenario A

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols (from Scenario A).
    - ***$12,175*** per year in labor and equipment savings (*calculated*)
- Reduced crashes from improved conditions due to RWIS presence (from Scenario A).
    - ***$186,227*** per year in crash cost savings (*calculated*)
- Reduced delay from improved conditions due to RWIS presence (from Scenario A).
    - ***$44,297*** per year in delay cost savings (*calculated*)

Intangible/Unquantified:

- Improved Traveler Information in areas that may have had no information.
- Improved information, especially camera images, for MDT Aeronautics and general aviation.

Costs

- Hardware
    - ***$8,000*** to ***$12,000*** per new simple site (*estimate*)
    - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 6.2*)

- ***$600*** yearly power and communications costs per site (*see Sec. 6.2*)

Benefit - Cost Ratio

- Agency: ***0.11*** to ***0.18***
- Total: ***2.1*** to ***3.6***

6.2.7. Scenario C (Observational, Non-Invasive Expansion)

This scenario includes using the current observational software with the current RWIS sites and 18 additional RWIS sites that use non-invasive sensors instead of in-pavement sensors.

Main Personnel Impacts

- Same as Scenario A

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols (from Scenario A).
  - ***$12,175*** per year in labor and equipment savings (*calculated*)
- Reduced crashes from improved conditions due to RWIS presence (from Scenario A).
  - ***$186,227*** per year in crash cost savings (*calculated*)
- Reduced delay from improved conditions due to RWIS presence (from Scenario A).
  - ***$44,297*** per year in delay cost savings (*calculated*)

Intangible/Unquantified:

- Possibility to store and review grip recovery type performance measures information for the 18 non-invasive sites.
- Improved Traveler Information in areas that may have had no information.
- Improved information, especially camera images, for MDT Aeronautics and general aviation.

Costs

- Hardware
  - ***$50,000*** to ***$60,000*** per new non-invasive site (*estimate*)
  - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 6.2*)
  - ***$600*** yearly power and communications costs per site (*see Sec. 6.2*)

Benefit - Cost Ratio

- Agency: ***0.05*** to ***0.07***
- Total: ***1.0*** to ***1.4***

6.2.8. Scenario D (Observational, Mobile Expansion)

This scenario includes using the current RWIS sites and 12 additional mobile RWIS sites[4]. Since the current software does not support mobile RWIS sensors, this scenario also includes obtaining a software product that supports mobile RWIS sensors. This scenario includes using mobile RWIS on maintenance vehicles during typical winter maintenance activities and not creating trips solely for mobile RWIS weather observation. Benefits in this and other "D" scenarios are limited by a lack of quantified information in the literature. Mobile RWIS coverage is fundamentally different from fixed site RWIS coverage, mainly due to the temporal availability of mobile RWIS observations being centered around storm response activities. This benefit model may be somewhat optimistic regarding the overall benefits of mobile RWIS as it quantifies only coverage related to winter maintenance activities and does not include any quantification of non-winter maintenance RWIS uses that may be better served by fixed sites.

Main Personnel Impacts

- Maintenance crews would have real-time conditions monitoring on any routes traveled by the 12 vehicles equipped with the mobile sensors.

Benefits

Documented / Estimable:

- Reduced labor and equipment use related to fewer patrols (from Scenario A).
    - Little to no patrolling savings would be realized from mobile sensor use as data is only gathered during maintenance vehicle travel.
    - ***$0*** per year in labor and equipment use savings (*estimated*)
- Reduced crashes from improved conditions due to RWIS presence (from Scenario A).
    - Depending on their geographical use areas, 12 mobile sensors would have similar coverage as 18 fixed sites, therefore similar coverage related benefits are used here.
    - ***$186,227*** per year in crash cost savings (*calculated*)
- Reduced delay from improved conditions due to RWIS presence (from Scenario A).
    - Depending on their geographical use areas, 12 mobile sensors would have similar coverage as 18 fixed sites, therefore similar coverage related benefits are used here.
    - ***$44,297*** per year in delay cost savings (*calculated*)

Intangible/Unquantified:

- Improved Traveler Information (similar to MDT snow plow cameras pilot project), but only during winter storm patrolling sensor use.

[4] Mobile RWIS estimated to have 1.5 times the geographic coverage of a fixed RWIS based on 25 mile coverage radius and 50 mph travel speed (see Appendix C). Therefore the 25% geographic expansion is 18 fixed RWIS or 12 mobile RWIS.

- Possibility to store and review basic mobile sensor grip level information.

Costs

- Software
  - Minimum
    - Hosted software service
      - ***$42,500*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)
      - ***$10,000*** initial migration (*see Sec. 6.2*)
  - Maximum
    - Hosted software service
      - ***$89,250*** per year (*vendors*)
      - ***-$10,000*** yearly O&M savings versus current (*see Sec. 6.2*)

- Hardware
  - ***$8,000*** to ***$18,500*** per new mobile sensor (*vendors*)
  - ***$2,000*** to ***$4,000*** yearly hardware and communications maintenance per site (*see Sec. 6.2*)
  - ***$600*** yearly power and communications costs per site (*see Sec. 6.2*)

Benefit - Cost Ratio

- Agency: ***No quantified agency specific benefits***
- Total: ***1.4*** to ***2.9***

6.2.9. Scenario 1-A (Observational + Alerting, Base Expansion)

This scenario includes using the base expansion sites with an alerting capable software.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & A except:

- The maximum software cost is increased to a hosted yearly cost of ***$91,000*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***0.1*** to ***0.2***
- Total: ***1.1*** to ***2.2***

6.2.10. Scenario 1-B (Observational + Alerting, Simple Expansion)

This scenario includes using the simple expansion sites with an alerting capable software.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & B except:

- The maximum software cost is increased to a hosted yearly cost of ***$91,000*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***0.2*** to ***0.4***
- Total: ***1.6*** to ***4.3***

6.2.11. Scenario 1-C (Observational + Alerting, Non-Invasive Expansion)

This scenario includes using the non-invasive expansion sites with an alerting capable software.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & C except:

- The maximum software cost is increased to a hosted yearly cost of ***$91,000*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***0.1*** to ***0.2***
- Total: ***1.0*** to ***1.7***

6.2.12. Scenario 1-D (Observational + Alerting, Mobile Expansion)

This scenario includes using the mobile expansion sites with an alerting capable software. Mobile RWIS monitoring software is also required.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 1 & D.

Benefit - Cost Ratio

- Agency: ***0.1*** to ***0.2***
- Total: ***1.8*** to ***3.7***

6.2.13. Scenario 2-A (Observational + Forecasting/MDSS, Base Expansion)

This scenario includes using the base expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options that provide forecasting and MDSS type information also typically have alerting functionality.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & A except:

- The minimum software cost is increased to an agency purchased software license of ***$532,000*** with a yearly vendor maintenance fee of ***$23,000*** per year (*vendors*)

Benefit - Cost Ratio

- Agency: ***5.7*** to ***8.5***
- Total: ***7.9*** to ***11.6***

6.2.14. Scenario 2-B (Observational + Forecasting/MDSS, Simple Expansion)

This scenario includes using the simple expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options that provide forecasting and MDSS type information also typically have alerting functionality.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & B except:

- The minimum software cost is increased to an agency purchased software license of ***$532,000*** with a yearly vendor maintenance fee of ***$23,000*** per year (*vendors*)
- The maximum software cost is increased to a hosted yearly cost of ***$173,800*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***6.9*** to ***12.2***
- Total: ***9.5*** to ***16.8***

6.2.15. Scenario 2-C (Observational + Forecasting/MDSS, Non-Invasive Expansion)

This scenario includes using the non-invasive expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options that provide forecasting and MDSS type information also typically have alerting functionality.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & C except:

- The minimum software cost is increased to an agency purchased software license of ***$532,000*** with a yearly vendor maintenance fee of ***$23,000*** per year (*vendors*)
- The maximum software cost is increased to a hosted yearly cost of ***$173,800*** (*vendors*)

Benefit - Cost Ratio

- Agency: ***4.8*** to ***7.3***
- Total: ***6.6*** to ***10.0***

6.2.16. Scenario 2-D (Observational + Forecasting/MDSS, Mobile Expansion)

This scenario includes using the mobile expansion sites with software that includes advanced forecasting and treatment suggestion type information. Software options for this scenario also include mobile RWIS support. Mobile RWIS, especially when coupled with Mobile Data Collection (MDC) / AVL technologies, may achieve substantial MDSS type benefits related to automated treatment feedback and improved forecasting, but that type of implementation is not included in this scenario as AVL was not desired as an alternative direction to investigate during consultation with the technical panel (Chien, et. al., 2014).

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 2 & D except:

- The software cost changes to a single option hosted yearly cost of ***$104,600*** (*vendors*)
- The minimum hardware cost changes to a single option of ***$18,500*** each (*vendors*)

Benefit - Cost Ratio

- Agency: ***~ 10.5***
- Total: ***~ 14.5***

6.2.17. Scenario 3-A (Observational + Performance Measures, Base Expansion)

This scenario includes using the base expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & A except:

- The software costs increase to ***$95,600*** per year (without forecasting) and ***$111,900*** per year (with forecasting) (*vendors*)

Benefit - Cost Ratio

- Agency (without forecasting): ***1.7*** to ***2.1***
- Total (without forecasting): ***8.4*** to ***10.3***

- Agency (with forecasting): ***6.7*** to ***8.2***
- Total (with forecasting): ***13.1*** to ***15.9***

6.2.18. Scenario 3-B (Observational + Performance Measures, Simple Expansion)

This scenario includes using the simple expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & B except:

- The software costs increase to ***$95,600*** per year (without forecasting) and ***$111,900*** per year (with forecasting) (*vendors*)

Benefit - Cost Ratio

- Agency (without forecasting): ***2.3*** to ***2.8***
- Total (without forecasting): ***11.2*** to ***13.8***

- Agency (with forecasting): ***8.9*** to ***10.7***
- Total (with forecasting): ***17.3*** to ***20.9***

6.2.19. Scenario 3-C (Observational + Performance Measures, Non-Invasive Expansion)

This scenario includes using the non-invasive expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & C except:

- The software costs increase to ***$95,600*** per year (without forecasting) and ***$111,900*** per year (with forecasting) (*vendors*)
- The non-invasive sensors in the expansion will increase the amount of the network that can benefit from the automated performance measures functionality.

Benefit - Cost Ratio

- Agency (without forecasting): ***3.7*** to ***4.5***
- Total (without forecasting): ***15.1*** to ***18.1***

- Agency (with forecasting): ***6.1*** to ***7.2***
- Total (with forecasting): ***17.0*** to ***20.2***

6.2.20. Scenario 3-D (Observational + Performance Measures, Mobile Expansion)

This scenario includes using the mobile expansion sites with a software and service capable of providing automated performance measures information. Like Scenario 3 this case considers a 25% retrofit of non-invasive sensors at existing sites.

Main Personnel Impacts, Benefits, and Costs

All personnel impacts, benefits and costs are the same as those included in Scenarios 3 & B except:

- The software costs increase to ***$89,300*** per year (without forecasting) and ***$104,600*** per year (with forecasting) (*vendors*)
- While mobile RWIS sensors can provide grip readings similarly to the non-invasive sensors, the automated performance measures currently available require wind sensors inputs which are not easily obtained on a moving vehicle. The automated performance measures also require reading at the same point over time to track changes and this may or may not be feasible depending on individual mobile sensor routes and travel times. The mobile RWIS included in this scenario therefore do not contribute to an increase in the amount of the network that can benefit from the automated performance measures functionality. Modified performance measures or in-house agency monitoring of basic grip information may be beneficial, but that is not quantified in this scenario.

<u>Benefit - Cost Ratio</u>

- Agency (without forecasting): ***~ 3.2***
- Total (without forecasting): ***~ 12.7***

- Agency (with forecasting): ***~ 10.1***
- Total (with forecasting): ***~ 19.7***

6.3. Summary

Many of the scenarios investigated show the promise of favorable benefit-cost ratios using the information and assumptions included in the analysis. All agency specific benefit-cost ratio ranges are shown in Table 9.

Table 9: Agency Specific Benefit-Cost Ratios

AGENCY	Current Software		1 (+Alerting)		2 (+F.cast)		3 (+P.M.) no F.cast		3 (+P.M.) with F.cast	
	min	max	min	max	min	max	min	max	min	max
Current Sites	Baseline		0.3	5.7	17.1	29.8	~ 4.8		~ 17.9	
A (+Base)	0.06	0.09	0.1	0.2	5.7	8.5	1.7	2.1	6.7	8.1
B (+Simple)	0.11	0.18	0.2	0.4	6.9	12.2	2.3	2.8	8.9	10.7
C (+N-I)	0.05	0.07	0.1	0.2	4.8	7.3	3.7	4.5	6.1	7.2
D (+Mob.)	NA		0.1	0.2	~ 10.5		~ 3.2		~ 10.1	

Agency specific benefits tend to outweigh the costs for all scenarios that utilize the current sensor locations when adding new functionalities. Advanced forecasting functionality may produce the highest agency savings, and alerting and automated performance measures functionalities may produce somewhat smaller, but still significant agency savings. All methods of RWIS coverage expansion tend to reduce the agency benefit-cost ratios somewhat when compared to using the current sites with improved functionalities alone.

When societal benefits are considered along with agency savings the benefit-cost ratios increase for all scenarios as shown in Table 10.

Table 10: Total (Agency + Societal) Benefit-Cost Ratios

TOTAL	Current Software		1 (+Alerting)		2 (+F.cast)		3 (+P.M.) no F.cast		3 (+P.M.) with F.cast	
	min	max	min	max	min	max	min	max	min	max
Current Sites	Baseline		1.0	20.6	20.5	36.0	~ 21.8		~ 33.3	
A (+Base)	1.2	1.8	1.1	2.2	7.9	11.6	8.4	10.3	13.1	15.9
B (+Simple)	2.1	3.6	1.6	4.3	9.5	16.8	11.2	13.8	17.3	20.1
C (+N-I)	1.0	1.4	1.0	1.7	6.6	10.0	15.1	18.1	17.0	20.2
D (+Mob.)	1.4	2.9	1.8	3.7	~ 14.5		~ 12.7		~ 19.7	

In general the most promising scenarios considering all benefits are:

- obtaining alerting functionality with no site expansion,
- obtaining automated performance measures, which require at least some current sites adding non-invasive sensors, and possibly expanding with new non-invasive sites,
- obtaining advanced forecasting functionality using the current sites, or
- obtaining both automated performance measures and advanced forecasting using the existing sites (with required non-invasive sensors) or the simple expansion sites or the non-invasive expansion sites, or the mobile expansion sites.

While certain scenarios reflect high benefit-cost ratios, their cost to implement will also be a factor in deciding what ultimately may be deployed. The minimum estimated first year and recurring costs are shown in Table 11. These values reflect the options with the minimum total present value over the total ten year analysis period.

Table 11: Minimum Estimated Costs ($ thousands, rounded to nearest thousand)

TOTAL	Current Software		1 (+Alerting)		2 (+F.cast)		3 (+P.M.) no F.cast		3 (+P.M.) with F.cast	
	1st yr	recur.	1st yr	recur.	1st yr	recur.	1st yr	recur.	1st yr	recur.
Current Sites	Baseline		21	0	492*	10*	427	67	440	80
A (+Base)	677	47	697	47	1,232	60	1,122	132	1,139	149
B (+Simple)	191	47	211	47	746	60	636	132	653	149
C (+N-I)	947	47	967	47	1,502	60	1,392	132	1,409	149
D (+Mob.)	170	64	170	31	222	31	567	111	582	126

* Fully hosted options are available with lower 1st year costs, but higher overall costs over ten year analysis period.

Most scenarios with the highest total benefit-cost ratios are also the most costly and may or may not be feasible with current MDT funding availability. Specifically, some of the most promising scenarios may require significant investments of hundreds of thousands of dollars above current RWIS funding amounts. One scenario, obtaining alerting functionality without expanding sites, is potentially both relatively low cost and highly beneficial, depending on the specific software product used.

7) SITE PRIORITIZATION MODEL

MDT, like many other state DOTs, continues to expand their RWIS program. As agencies expand their RWIS programs, they are often faced with the challenge of selecting a limited number of ESS sites from a larger pool of proposed sites given the limited budgets available. Traditionally, regional and statewide ESS site selection has typically been a subjective process relying primarily on DOT personnel and meteorologist judgement. Therefore, there is a need for an objective prioritization model for proposed ESS, which should guide future RWIS expansion and ensure maximum utility (benefits) from new ESS installations.

The work performed in this task and presented in this chapter aims at developing a model for assessing the merit of proposed new ESS sites which could serve as a guide for RWIS system expansion in a region or at the state level. Such a model can help MDT in prioritizing the installation of new ESS sites on a regular basis. The model may also be used in finalizing the exact location of a proposed site along a specific corridor to ensure an optimum output is obtained.

7.1. Site Prioritization Model Definition

In any given year, multiple sites may be proposed for installation of new ESS as part of an RWIS system expansion. Given that there are limited resources available, an agency is usually required to select only a few sites out of the proposed list of sites where weather data is deemed most needed. This process has traditionally been subjective in nature, and agency personnel may have to attempt to create semi-objective rankings for the proposed sites to help them in making siting decisions. Objective rankings would require the consideration of many factors that are all important in determining the merit of ESS installation at a particular site. In this research, the proposed scheme for assessing the merit of a proposed ESS site takes into account the following considerations:

- Weather conditions,
- Highway network served,
- Expected safety benefits,
- Geographic coverage of ESS sites, and
- Other opportunistic factors

Each of the above considerations is discussed briefly in the following sections.

<u>Weather Conditions</u>

Weather is one of the most important determinants of merit for new ESS sites. Both severity and variability in meteorological conditions are important considerations in this determination. From the severity perspective, weather data is more valuable and satisfies a larger need in areas where extreme winter weather conditions exist. For example, information on the form (snow, ice, rain, etc.) and amount of precipitation is critical for winter maintenance operations and intelligent transportation system (ITS) safety applications. The variability of weather conditions in the area surrounding a proposed site is also important in assessing the need for a new adjacent ESS sites. Specifically, if weather conditions do not vary significantly in the areas surrounding a proposed site, then information from the existing ESS site may reasonably be used in predicting weather conditions at the location of proposed surrounding sites. However, this may prove to be impractical should significant variability in weather conditions exist in the area surrounding the proposed site, such as when topography and terrain notably change over a relatively short distance.

Highway Network Served

RWIS programs are primarily intended to provide weather data for the highway system and its associated applications. As such, the role of an ESS in remote areas where no or few well-traveled highways exist may not be as significant as that of a station that is located in more developed area with multiple well-traveled highways surrounding the ESS site.

Expected Safety Benefits

Adverse weather conditions can negatively affect safety on highways and result in higher frequencies of weather-related crashes. The availability of real-time weather data is critical for highway agencies to ensure safer roads by providing timely winter maintenance and/or alerting drivers to hazardous situations via traveler information systems and ITS warning devices. Therefore, higher instances of weather-related crashes along highway segments surrounding a proposed site may reflect a need for timely weather data.

Geographic Coverage of ESS Sites

Another consideration in assessing the need for a new ESS site is the geographic coverage of existing ESS sites in the area. In areas where ESS are sparse and farther apart, the need for new installations becomes more evident as weather data there may be especially valuable in the absence of other ESS. If an area is well served by existing ESS then there may be less value in installing additional ESS nearby.

Other Opportunistic Factors

Power and communications are essential for the operation of ESS. Therefore, the availability and ease of access to power and communications often have implications on installation costs and feasibility and should be considered in assessing the merit of a proposed ESS site.

7.2. Structure of the Proposed Model

In this section, the formulation of the proposed model is discussed along with the procedures developed for quantifying different model variables. The overall merit (OM) is a rank on a scale of 0 to 1.0 which will serve as an indicator of the merit (or the need) associated with a proposed new site. The overall merit can be calculated using the following equation:

$$\mathbf{OM = w_1\,(WI) + w_2\,(CI) + w_3\,(TI) + w_4\,(GC) + w_5\,(OF)}$$

Where:

WI: Weather index,
CI: Crash index,
TI: Traffic index,
GC: Geographic coverage index,
OF: Opportunistic (situational) factors, and
w_1, w_2, w_3, w_4 and w_5: weights associated with model variables which should be selected to reflect the agency preferences and priorities.

7.2.1. Weather Index

The weather index accounts for all meteorological variables that are deemed important in a new ESS installation. As discussed earlier, those variables are indicators of the severity and variability in weather conditions at a proposed site. The weather index is calculated using the following equation:

$$\mathbf{WI = a_1 (FT) + a_2 (RF) + a_3 (SI) + a_4 (TG) + a_5 (SG)}$$

Where:

FT: Freezing Temperature, measured as the proportion of time during the year with minimum temperature below 32 degrees Fahrenheit;
RF: Annual rainfall accumulation score;
SI: Monthly snowfall intensity score;
TG: Temperature relative gradient score;
SG: Snowfall relative gradient score; and
a_1, a_2, a_3, a_4 and a_5: weights associated with model variables which should be selected to reflect the agency preferences and priorities

The first variable in the above equation, FT, is calculated as the number of months during the year with average minimum temperature less than 32 degrees divided by 12 (months in a full year). The second variable, RF, is a score which represents the expected total annual accumulation of rainfall at the proposed ESS site. SI represents the average snowfall intensity at the proposed ESS site during the months of the year with snowfall accumulation in excess of two inches. The aforementioned three variables all represent the magnitude of weather attributes at a proposed ESS site. The other two variables in the equation above, TG and SG, are related to weather variability in the area surrounding a proposed ESS site. Specifically, TG is a score which represents the average temperature relative gradient between a proposed site and surrounding existing weather stations and is calculated as follows:

$$TG = \sum_{i=1}^{n} [(T_P - T_i) / D] / n$$

Where T_p & T_i are the annual average mean temperature for the proposed and nearby station respectively, D is the distance between stations in miles, and n is the number of existing stations surrounding the proposed ESS site. For the purpose of this research, surrounding stations within a 15-mile radius circle are considered in this calculation.

The last variable in the weather index equation is SG which is a score representing the average snowfall relative gradient between a proposed site and surrounding existing weather stations and is calculated using the following equation:

$$SG = \sum_{i=1}^{n} [(S_P - S_i) / D] / n$$

Where S_p & S_i are the annual average snowfall accumulation for the proposed and nearby station respectively, D is the distance between stations in miles, and n is the number of existing weather stations surrounding the proposed ESS site. Again, surrounding stations within a 15-mile radius circle are considered in this calculation.

The scoring schemes used for variables RF, SI, TG and SG are summarized in Table 12. The values shown in the table were developed considering weather conditions throughout the state of Montana.

Table 12: Scoring scheme for variables RT, RS, SI and RF

Score	TG (degrees/mile)	SG (inches/mile)	SI (inches/month)	RF (inches)
0.1	< 0.10	< 1.0	< 3.0	< 5.0
0.2	0.10 - 0.15	1.0 - 1.8	3.0 - 4.5	5.0 - 7.5
0.3	0.15 - 0.20	1.8 - 2.6	4.5 - 6.0	7.5 - 10.0
0.4	0.20 - 0.25	2.6 - 3.4	6.0 - 7.5	10.0 - 12.5
0.5	0.25 - 0.30	3.4 - 4.2	7.5 - 9.0	12.5 - 15.0
0.6	0.30 - 0.35	4.2 - 5.0	9.0 - 10.5	15.0 - 17.5
0.7	0.35 - 0.40	5.0 - 5.8	10.5 - 12.0	17.5 - 20.0
0.8	0.40 - 0.45	5.8 - 6.6	12.0 - 13.5	20.0 - 22.5
0.9	0.45 - 0.50	6.6 - 7.4	13.5 - 15.0	22.5 - 25.0
1.0	> 0.50	> 7.4	> 15.0	> 25.0

Weather Index Model Validation

To test the ability of the weather index model in forecasting weather conditions at a proposed EES site, the model was applied to a selected sample of existing weather stations that were treated as hypothetical new sites in Montana. First, a predicted weather index was developed at those selected sites using weather information from surrounding stations only as well as weather predictions using published temperature and precipitation contour maps for the state of Montana. Then, the weather index was calculated using actual weather information from the selected sites (referred to later as actual WI). The two values (predicted and actual) are compared and the percentage difference is determined. In this analysis, equal weights were assigned to the five WI model variables ($a_1=a_2=a_3=a_4=a_5=0.2$). Table 13 shows the selected sample weather stations used in model validation.

Table 13: Selected Sample Weather Stations Used in Model Validation

Station	Lat.	Long.	Distance (miles)	Station	Lat.	Long.	Distance (miles)
LIBBY 1 NE RS	48.24 N	115.32	0	CROW AGENCY	45.36 N	107.27	0
LIBBY DAM BASE	48.25 N	115.19	6.21	HARDIN	45.44 N	107.37	3.73
TROY	48.29 N	115.54	10.56	HYSHAM 25 SSE	45.56 N	107.08	8.7
HERON 2 NW	48.04 N	115.59	18.64	CONTENT 3 SSE	47.59 N	107.33	0
DRUMMOND AVIATION	46.38 N	113.11	0	MALTA 35 S	47.51 N	107.57	6.84
OVANDO 9 SSE	46.54 N	113.04	11.81	MOSBY 4 ENE	47.01 N	107.49	21.75
POTOMAC	46.53 N	113.34	14.9	WESTERN AG RESEARCH	46.19 N	114.07	0
PHILIPSBURG R S	46.18 N	113.18	14.3	STEVENSVILLE	46.31 N	114.05	4.35
JUDITH GAP 13 E	46.40 N	109.29	0	HAMILTON	46.14 N	114.1	1.86
JUDITH GAP	46.41 N	109.45	7.46	GLASGOW INTL AP	48.13 N	106.37	0
RYEGATE 18 NNW	46.32 N	109.21	6.84	GLASGOW 14 NW	48.21 N	106.51	4.35
LEWISTOWN 11 SSE	46.54 N	109.25	9.94	FORT PECK POWER PLANT	48.01 N	106.25	5.6
LAME DEER	45.38 N	106.4	0	SACO 1 NNW	48.28 N	107.21	0
COLSTRIP	45.54 N	106.38	11.18	FORKS 4 NNE	48.47 N	107.27	7.46
BUSBY	45.32 N	106.58	9.94	WHITEWATER	48.46 N	107.37	8.07
BRANDENBERG	45.49 N	106.14	14.9	MALTA 7 E	48.24 N	107.44	5.6
BIRNEY	45.19 N	106.31	13.67	HARB	48.14 N	107.25	5.6
BELGRADE AP	45.48 N	111.09	0	HINSDALE 4 SW	48.21 N	107.09	3.73
BOZEMAN 6 W EXP FARM	45.41 N	111.09	4.97	MEDICINE LAKE 3 SE	48.29 N	104.27	0
BOZEMAN MSU	45.40 N	111.03	6.21	WESTBY	48.52 N	104.03	10.56
TRIDENT	45.57 N	111.28	11.18	CULBERTSON	48.09 N	104.31	7.46
JORDAN	47.19 N	106.55	0	REDSTONE	48.49 N	104.57	10.56
HAXBY 18 SW	47.34 N	106.42	11.81	PLENTYWOOD	48.47 N	104.33	6.84
JORDAN 23 ENE	47.29 N	106.28	14.29	DENTON	47.19 N	109.56	0
COHAGEN	47.03 N	106.37	13.67	WINIFRED	47.34 N	109.23	9.94
KALISPELL GLACIER	48.18 N	114.16	0	LEWISTOWN MUNI AP	47.03 N	109.28	9.32
WHITEFISH	48.25 N	114.22	5.6	MOCCASIN EXP STN	47.03 N	109.57	6.21
CRESTON	48.11 N	114.08	6.21	ILIAD	47.48 N	109.49	11.18
HUNGRY HORSE DAM	48.21 N	114.01	7.46	LIBBY 1 NE RS	48.24 N	115.32	0
RUDYARD 27 N	48.56 N	110.34	0	LIBBY DAM BASE	48.25 N	115.19	6.21
SIMPSON 6 NW	48.59 N	110.18	4.35	TROY	48.29 N	115.54	10.56
GILDFORD	48.34 N	110.18	9.32	TROY 18 N	48.43 N	115.53	8.7
				HERON 2 NW	48.04 N	115.59	18.64

The highlighted cells represent the selected stations and surrounding stations are listed underneath each site. A total of sixteen sites were selected from various regions in the state with different numbers of surrounding stations.

Validation results are shown in Table 14. The second and third columns show the calculated weather index based on predicted and measured weather information respectively. The fourth column in this table is of particular importance as it shows the difference between the predicted and actual weather indices expressed as a percentage. The last column in this table shows the number of surrounding weather stations used in WI calculation.

Table 14: Validation Results of Proposed Weather Index Model

Proposed Site	Predicted WI	Actual WI	Percent Difference	Number of Surrounding Stations
LIBBY 1 NE RS	0.420	0.440	5	3
DRUMMOND AVI	0.397	0.377	5	3
JUDITH GAP 13 E	0.417	0.473	12	3
LAME DEER	0.337	0.317	6	4
BELGRADE AP	0.480	0.457	5	3
JORDAN	0.277	0.280	1	3
KALISPELL GLACIER	0.380	0.397	4	3
RUDYARD 27 N	0.380	0.297	28	2
CROW AGENCY	0.473	0.557	15	2
CONTENT 3 SSE	0.303	0.247	23	2
WESTERN AG RSCH	0.380	0.400	5	2
GLASGOW INTL AP	0.383	0.423	10	2
SACO 1 NNW	0.277	0.297	7	5
MEDICINE LAKE 3 SE	0.317	0.297	7	4
DENTON	0.397	0.437	9	4
LIBBY 1 NE RS	0.440	0.460	4	4

The overall average difference between the predicted and actual weather index is approximately 9% at all sites with the highest value being 28%. The difference exceeded 10% at four out of sixteen sites, i.e. at 25% of the sites. A closer look at those sites clearly shows that the highest three values belong to sites that are surrounded by only two nearby weather stations that were used in WI calculations, and the fourth highest value at a site surrounded by three nearby stations. This observation implies a potential relationship between the accuracy of WI predictions and the number of surrounding weather stations used in WI calculations. To test this possibility, the relationship between percent difference and the number of surrounding stations was plotted and the best fit linear curve was established as shown in Figure 55. While observations are scattered, the general trend supports the tentative relationship, i.e. the more surrounding stations used in calculations, the less the difference between the predicted and actual weather indices. The coefficient of correlation was found to be -0.49, which is consistent with the assumed relationship and the trend shown in Figure 55.

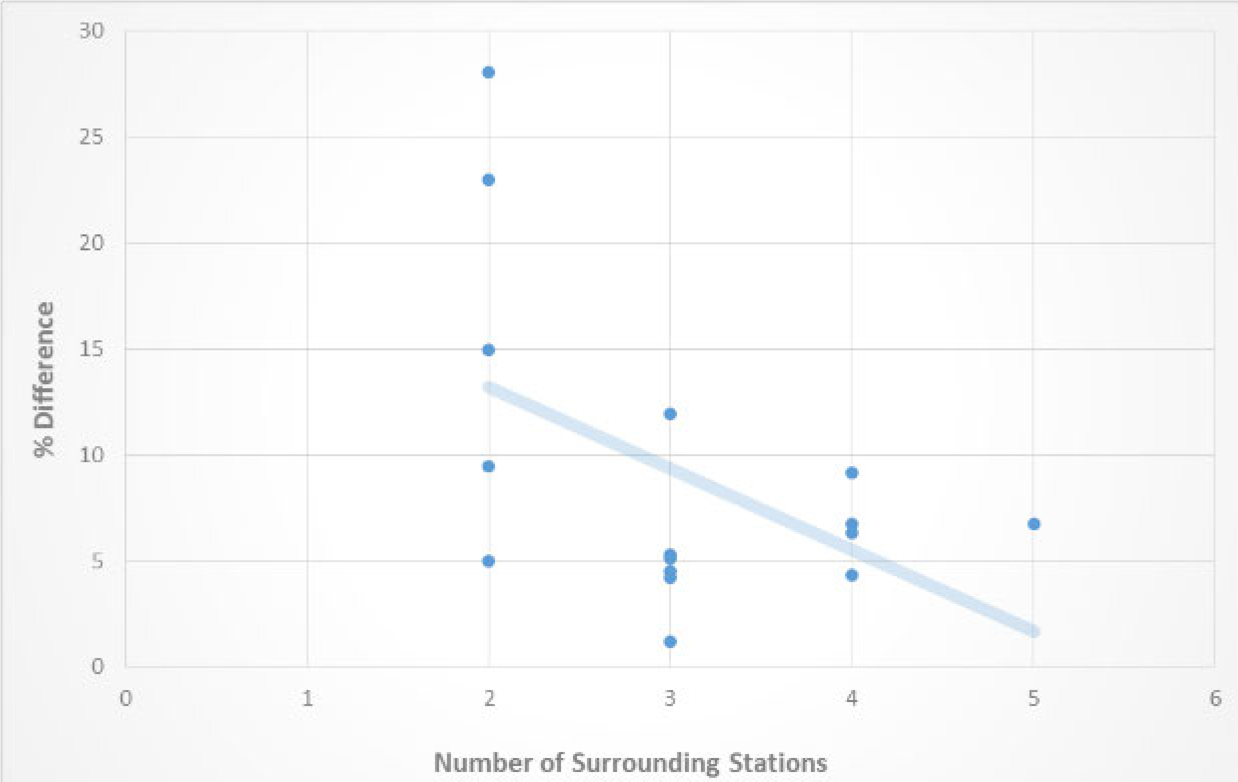


Figure 55: Percent Difference versus Number of Surrounding Stations

7.2.2. Traffic Index

A major consideration in the siting of a new ESS is the amount of traffic that is expected to benefit from the weather information produced by a proposed ESS site. In general, the amount of traffic is largely a function of the highway network surrounding the weather station and the functional class of highways in the network. The amount of travel expressed in million vehicle miles of travel (MVMT) within a 30-mile diameter circle around the proposed site was used to account for traffic variables. The amount of travel was calculated using the Annual Average Daily Traffic (AADT) and segment length for all highways in the network except local roads using the following equation:

$$\text{MVMT} = \frac{\sum_{i=1}^{n}(AADTi * 365 * Li)}{1000000}$$

Where:

$AADT_i$ = Annual average daily traffic for segment i

L_i = Length of segment i

n = Number of segments within the 30-mile circle surrounding proposed ESS site

A scoring scheme for the amount of travel was developed using travel information for the state of Montana as shown in Table 15.

Table 15: Amount of Travel Scoring Scheme

MVMT	TI
0 - 50	0.1
50 - 100	0.2
100 150	0.3
150 - 200	0.4
200 - 250	0.5
250 - 300	0.6
300 - 350	0.7
350 - 400	0.8
400 - 450	0.9
> 450	1.0

7.2.3. Crash Index

Another consideration in assessing the merit of a new ESS is the safety of the route along which a proposed site is located. It is logical to expect that routes with high crash experience and high proportions of weather-related crashes to benefit more from weather information produced by a proposed ESS site.

In this research, crash rate per MVMT along a 20-mile segment of the route where the proposed ESS is located and the percentage of weather-related crashes are used in calculating the crash index. The aforementioned segment extends 10 miles upstream and 10 miles downstream of the proposed site. Crash severity is accounted for in calculating crash rate by using Equivalent Property Damage Only (EPDO) crashes where different weights are assigned to injury and fatal crashes. Once all crashes are converted to EPDO crashes and using the AADT for all sections comprising the 20-mile segment route, crash rate (CR) can be calculated using the following equation:

$$CR = \frac{C*100{,}000{,}000}{\sum_{i=1}^{n} 365*AADTi*T*Li} \tag{9}$$

Where C is the total number of EPDO crashes on the 20-mile evaluation segment, $AADT_i$ is the Annual Average Daily Traffic for section i, T is the evaluation time period in years, Li is the length of section i, and n is the number of sections in the 20-mile segment.

While crash history overall is important in assessing the merit of installing new ESS, weather-related crashes are of particular importance. To account for inclement weather risks along the route, the percentage of weather-related crashes (PW) is used in developing adjusted crash rate (CR_{adj}) using the following equation:

CR_{adj} = MAX [(CR), (CR) * (1+ (PW-0.15))]

Where

CRadj = Adjusted crash rate (to account for weather related crashes,
CR = Crash rate (EPDO per 10 MVMT), and

PW = Percentage of weather-related crashes to total crashes

The "0.15" used in the equation above is based on the average of weather-related crashes at a sample of roadway sites in Montana which was found to be around 10%. A different value could be used in the model should a more accurate percentage of weather-related crashes in Montana becomes available (e.g. statewide average).

Using crash statistics in the state of Montana, a scoring scheme was developed to convert the adjusted crash rate to a crash index (CI) to be used in the overall merit model as shown in Table 16.

Table 16: Crash Experience Scoring Scheme

Crash Rate (Crashes per MVMT)	Crash Rate Score (CRS)
< 10	0.1
10 - 20	0.2
20 - 30	0.3
30 - 40	0.4
40 - 50	0.5
50 - 60	0.6
60 - 70	0.7
70 - 80	0.8
80 - 90	0.9
> 90	1.0

7.2.4. Geographic Coverage Index

Another aspect of assessing the merit of proposed ESS sites is the area coverage by existing weather stations. Specifically, areas and regions that have sparse weather stations may be good candidates for new ESS installations. Similarly, if an area is well served by existing ESS then there may be less value in installing additional ESS nearby. In this assessment, both RWIS and non-RWIS weather stations should be considered. However, the fact that RWIS stations are directly located along important routes while non-RWIS stations are usually located at some distance from surrounding highways, the two types should be treated differently.

To assess the geographic coverage of ESS sites in the proposed model, the state of Montana was divided into uniform units of area using a 30X30 miles grid, and weather station coverage was then established and expressed as the number of square miles per station, i.e. the larger the number the lower the coverage. Figure 56 shows weather stations in the state of Montana using the 30 by 30 mile grid lines. The stars refer to existing RWIS stations, while dots refer to other weather stations.

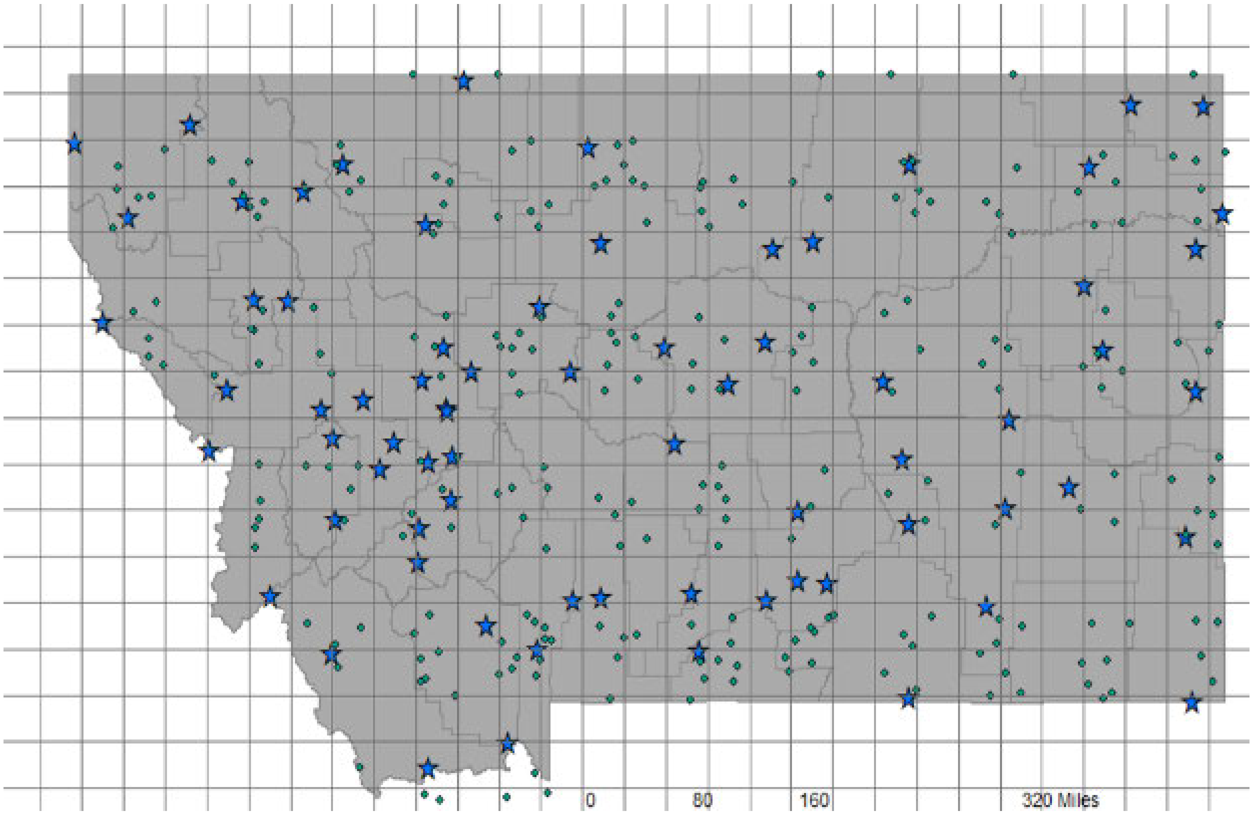


Figure 56: Weather Stations in the State of Montana using 30 by 30 Miles Grid Lines.

Each non-RWIS station was treated as 0.7 RWIS station in calculating coverage, given the higher utility expected from RWIS stations in supporting transportation applications. The area of a single grid unit (900 square miles) is then divided by the number of weather stations to determine coverage. Using data from the state of Montana shown in Figure 56 above, a scoring scheme from 1 to 5 was developed to assess the coverage at a particular proposed site (see Table 17 below).

Table 17: Scoring scheme for ESS coverage

ESS Coverage mile^2/station	Coverage Type	GC
> 1300	No-coverage	1.0
1000 - 1300	Poor	0.8
800 - 1000	Fair	0.6
400 - 800	Good	0.4
100 - 400	Very good	0.2

7.2.5. Opportunistic Factors

As discussed earlier, the availability of power and communications infrastructure should add to the merit of a proposed ESS site, and the lack of power, communications or both should negatively affect the merit of a proposed site. While the availability of grid power at a proposed site is always a plus, the use of solar panels at isolated sites is possible and may provide a feasible alternative. In regards to communications, the lack of wireless mobile network or telephone lines at a proposed site may require additional infrastructure to be installed, a solution that may prove to be costly.

The opportunistic factors scoring scheme developed consists of four different scenarios and associated scores as shown in Table 18 below.

Table 18: Opportunistic Factors Scoring Scheme

Grid Power?	Cell / Phone Communications?	OF
YES	YES	1.0
NO	YES	0.8
YES	NO	0.4
NO	NO	0.0

7.3. Application of the Model

To demonstrate the application of the proposed ESS merit model, five hypothetical sites in the state of Montana were selected to represent different regions, highway class and weather conditions. Information on selected sites from MDT records is provided in Table 19 and the location of sites on the state county map is shown in Figure 57.

Table 19: Description of Selected Sites per MDT Records

Site No.	MDT Department Route.	MDT Corridor Route.	MDT Site ID	County or City	Latitude	Longitude
1	N-1	C000001	53-4-2	Glasgow	48.1952	-106.63
2	P-205	C000205	16-3-32	Gallatin	45.679	-111.041
3	N-57	C000057	14-6-5	Lewistown	47.071	-109.439
4	N-5	C000005	15-7B-18	Flathead	48.183	-114.308
5	I-90	C000090	56-4A-4	Billings	45.787	-108.493

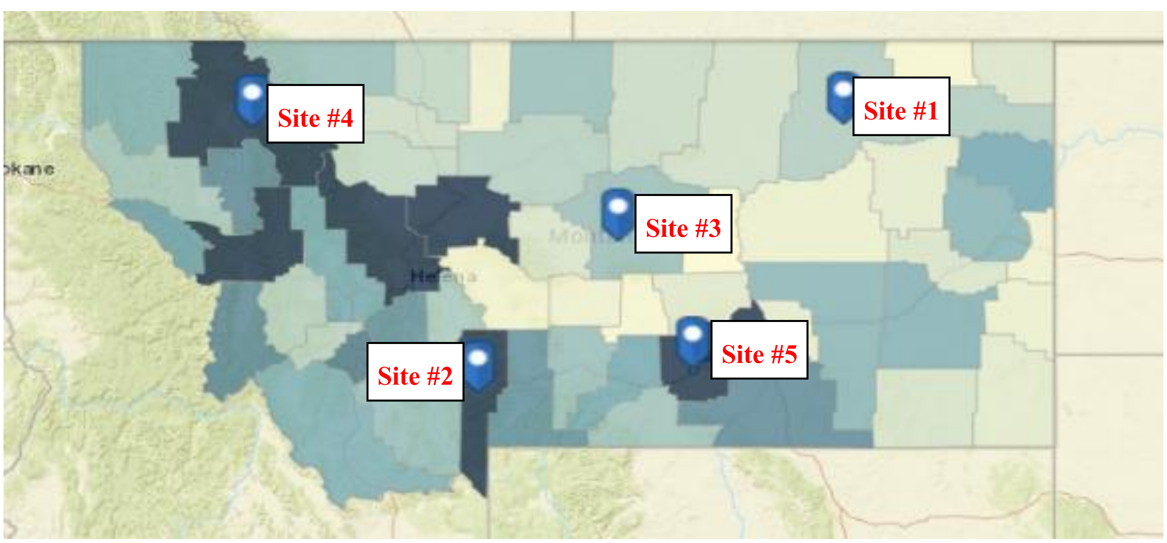


Figure 57: Selected Sites on Montana County Map

Information on selected sites were gathered, variables were calculated using the equations and charts used in the proposed procedure, and the overall merit of sites were determined using the OM model. All sites were assumed to have access to grid power and mobile communication network. Equal weights ($w_1 = w_2 = w_3 = w_4 = w_5 = 0.2$) were used for model variables in this sample application. Results of the analysis are presented in Table 20. Sample calculations and data sources for site #2 are included in Appendix D.

Table 20: Application of Proposed Model on Selected Sites

Site No.	MDT Route.	WI	TI	GC	CI	OF	Overall Merit	Rank
1	N-1	0.323	0.1	0.4	0.4	1.0	0.4446	4
2	P-205	0.397	1.0	0.4	0.4	1.0	0.6394	2
3	N-57	0.477	0.1	0.2	0.4	1.0	0.4354	5
4	N-5	0.537	0.6	0.4	1.0	1.0	0.7074	1
5	I-90	0.283	1.0	0.2	0.4	1.0	0.5766	3

As can be seen in Table 20, installing an ESS at site #4 is expected to provide most utility (benefits) followed by site #2, site #5, site #1 and site #3 respectively.

7.4. Concluding Remarks

The model developed and presented in this chapter provides a methodology for prioritizing proposed ESS sites in a state or region by assessing the merits of those sites using weather, traffic and safety data among other variables. Inputs to the proposed model include weather index, traffic index, crash index, geographic coverage and opportunistic factors. The weather index at a proposed site is determined using multiple indicators of weather severity and variability. The proposed crash index incorporates crash rate along the route where the ESS is located and the percentage of weather related crashes over the analysis period. The third input to the merit model, the traffic index, reflects the amount of travel on the highway network in the area surrounding the proposed ESS site. The fourth input to the merit model accounts for the ESS existing coverage in the area where the proposed site is located while the fifth and last input accounts for the availability and ease of access to power and communications. Model coefficients are represented by weights assigned to different model inputs which reflect the contribution of each input (variable) to the overall merit of the ESS site. Those weights are user-specified and should be selected to reflect the agency preferences and priorities. A demonstration of the application of the proposed model was presented using a selected number of sites in different parts throughout the state of Montana.

8) CONCLUSIONS AND RECOMMENDATIONS

A number of findings have come of this overall assessment of MDT's RWIS program. This chapter will review the major conclusions from each project task and culminate in some recommendations stemming from the project work.

Selected observations from each task include:

State of the Art Review

- RWIS programs have expanded and evolved since their initial primary focus of winter maintenance support to include other uses and users including traveler information, operations activities, advanced ITS applications, and third-party weather service providers.
- RWIS technologies are now available from many vendors and manufacturers, and agencies are beginning to desire and require open architecture and flexible systems to allow for the use of technologies from more than a single provider.
- Traditionally ESS siting was a subjective process relying solely on personal judgement, and some agencies are starting to define systematic, objective ESS placement methods that attempt to quantify and optimize the knowledge held by agency personnel; optimization models using data related to winter crash history, traffic volumes, and historical climate data are now being proposed.
- Overall the literature suggests RWIS programs produce many benefits that outweigh the costs; agency specific benefits like labor, materials, and equipment cost savings have benefit-cost ratios ranging from 1.1:1 up to 11:1, and when safety, operational, and other societal benefits are also considered the benefit-cost ratios increase and can exceed 40:1.

State of the Practice Review

- RWIS data are now used for purposes including weather-responsive ITS and tracking weather-related performance metrics, but remain primarily focused on winter maintenance support.
- Operational data like traffic speeds, traffic volumes, and vehicle classifications, are not widely collected at most agencies' RWIS sites, but a couple of agencies do collect operational data at most/all RWIS locations.
- A few agencies have begun utilizing mobile RWIS as "non-trivial" portions of their program, and many others have begun to experiment with or use limited mobile RWIS equipment.
- Current funding and effort levels toward mobile RWIS remain low overall compared to traditional RWIS, but are anticipated to increase in the next five years.
- Many agencies collect mobile maintenance vehicle data (i.e. plow data, spreader data, Canbus data), but only a few integrate that into their larger RWIS efforts.
- RWIS site placement is most commonly determined using agency personnel expertise, but some examples of other methods were cited including the use of geo-spatial analyses considering crash histories, climate historical data, and traffic levels / road classifications as well as using public input, academic and consultant research, and thermal mapping analysis.

- Certain RWIS data types were thought to be almost unanimously essential including: pavement temperature, air temperature, pavement condition, wind speed and direction, and precipitation occurrence. Other data types that were thought to be at least helpful on average include: precipitation intensity/depth, humidity, precipitation type, visibility, still camera images, freeze temperature, chemical presence, friction, barometric pressure, and chemical concentration.
- Non-proprietary RWIS controllers and communications were required by five (5) of the responding agencies and desired in another eleven (11) agencies.
- Overall RWIS programs are still expanding with most agencies adding more sites for additional geographic coverage, many agencies enhancing existing locations with additional sensors, and some agencies adding mobile RWIS.
- In general, most agencies support the idea that more RWIS stations with fewer sensors (i.e. camera and pavement temperature only) would be better than fewer sites with their current configurations if made possible by cost savings using fewer sensors per site.
- Agency developed, custom software and Vaisala products are the most common software for displaying RWIS data for the responding agencies, but Delcan and Lufft were also cited.
- Typically RWIS software and hardware are operated and maintained either by agency personnel, Vaisala, or a combination of the two; other vendors (Lufft, Delcan and Narwhal Group) also perform these functions in a few responding agencies.
- Responses to open ended feedback found many respondents emphasizing the need for RWIS data display software on mobile devices, and improvements in using more mobile RWIS, non-invasive sensor technology, and non-proprietary systems.

Needs Assessment

- Maintenance personnel need camera images, pavement conditions, air temperature, pavement temperature, wind speed and direction, precipitation type and occurrence, and visibility.
- All stakeholder groups generally favor the idea of having more sites with only a camera and pavement temperature sensor compared to fewer sites with more sensors per site; maintenance personnel may also need wind sensors or visibility sensors only at certain locations.
- It may be beneficial to update camera images and RWIS data every 15 minutes.
- The most problematic pieces of equipment from a maintenance perspective, the PTZ cameras, are also the most valuable.
- Cellular communications are the main source of RWIS data outages and those outages are out of MDT’s control.
- There are certain sensor and camera technologies that may be desired including non-invasive sensors, more robust precipitation sensors, visibility sensors, live video, and cameras with the ability to produce images in the dark.
- The ability to display RWIS data for maintenance personnel on mobile devices is desired, but may be partially available currently via the traveler information mobile app.
- More RWIS sites are desired overall and especially near maintenance section boundaries.
- Mobile RWIS are not generally desired at the section supervisor / maintenance superintendent level, but more interest is shown at the maintenance chief level.

- Required RWIS software and server upgrades have recently resulted in some specific functionality losses, namely those related to condition and status alerts.
- RWIS data is widely used by the public via the traveler information systems accessible via MDT website.
- The public (via traveler information) may be the most common method for the agency to learn of unavailable or malfunctioning sensors and sites.
- Cameras are the most popular type of information for the public who would presumably prefer more camera-only sites compared to fewer fully-instrumented sites.
- RWIS is a secondary data source for the Aviation Division and general aviation uses in Montana; camera images with horizon views and especially those near mountain passes may be the most valuable RWIS information for aviation.

Weather Data and Software Analysis

- MDT's RWIS program currently includes 73 ESS providing data for winter maintenance personnel and traveler information systems within MDT as well as sharing the data outside MDT to 511-provider Iteris, NOAA, and MSU/WTI for multistate traveler info/operations systems.
- The core sensor setup that exists at virtually all 73 ESS includes an air temperature and humidity sensor, wind speed and direction sensor, in-pavement sensor, subsurface temperature sensor, precipitation occurrence sensor, and a camera; select sites (6 or fewer) also have advanced precipitation sensors, visibility sensors, or infrared illuminators for nighttime camera images.
- MDT's internal RWIS software for data polling, processing and display is a legacy Vaisala system (SCAN Web 6.0) that no longer has the ability to provide weather condition or sensor/site status alarms, limited usability on mobile devices, and no forecasting functionality.
- Alternative sensors including various atmospheric combination sensors, infrared lights for cameras, visibility sensors, advanced precipitation sensors, and non-invasive sensors are available and may provide additional functionality or configuration options compared to the current core sensor setup.
- Many alternative RWIS software systems exist, categorized by their functionality from basic observational only software to those with options for alerting, forecasting, mobile sensor integration and automated performance metric functionalities.

Benefit-Cost Analysis

- Agency specific benefits exceed costs for all three alternative software systems (alerting, forecasting and automated performance metrics) when considering the current ESS sites.
- The highest agency specific benefit-cost ratios were found to be possible with forecasting and automated performance metric functionalities.
- Total benefits including societal benefits exceed costs for all ESS expansion options (base, simple, non-invasive, and mobile) and all alternative software systems (alerting, forecasting and automated performance metrics).
- The highest total benefit-cost ratios were found to be possible with forecasting and automated performance metric functionalities.
- Overall the most promising scenarios considering all benefits are:

  - obtaining alerting functionality with no site expansion,
  - obtaining automated performance measures, which require at least some current sites adding non-invasive sensors, and possibly expanding with new non-invasive sites,
  - obtaining advanced forecasting functionality using the current sites, or
  - obtaining both automated performance measures and advanced forecasting using any of the ESS site expansion scenarios.
- Most scenarios with the highest total benefit-cost ratios are also the most costly and may or may not be feasible with current MDT funding availability.
  - Some of the most promising scenarios may require significant investments in the order of hundreds of thousands of dollars above current RWIS funding amounts.
  - One scenario, obtaining alerting functionality without expanding sites, is potentially both relatively low cost and highly beneficial, depending on the specific software product used.

Site Prioritization Model

- A model has been established to increase the objectivity of ESS site selection to assist MDT.
- The model quantifies the overall merit of potential ESS sites based on historical weather conditions, traffic amounts, crash history, existing geographic coverage and opportunistic factors related to the availability of power and communications.
- This model is customizable and allows MDT to place selected weights on certain aspects according to their agency priorities.

Recommendations

Considering the overall project and the findings from project tasks, the researchers recommend the following:

- Consider requiring or encouraging new RWIS sensor, hardware, and software options be as flexible as possible through the use of non-proprietary communications and compatibilities.
- Reduce the RWIS data and camera image update interval to 15 minutes or less for all sites.
- Include a horizon view for aviation users at all ESS with PTZ cameras.
- In areas that currently have little or no RWIS coverage, make maintenance personnel aware of resources like http://mesowest.utah.edu/ that may have additional weather information from non-RWIS sites.
- Utilize the proposed site prioritization model with agency selected weights to plan future RWIS installations.
- The future directions shown in Figure 58 and discussed below, should be considered depending on the budget available for implementing RWIS program changes and the potential acceptance of somewhat different winter maintenance procedures.

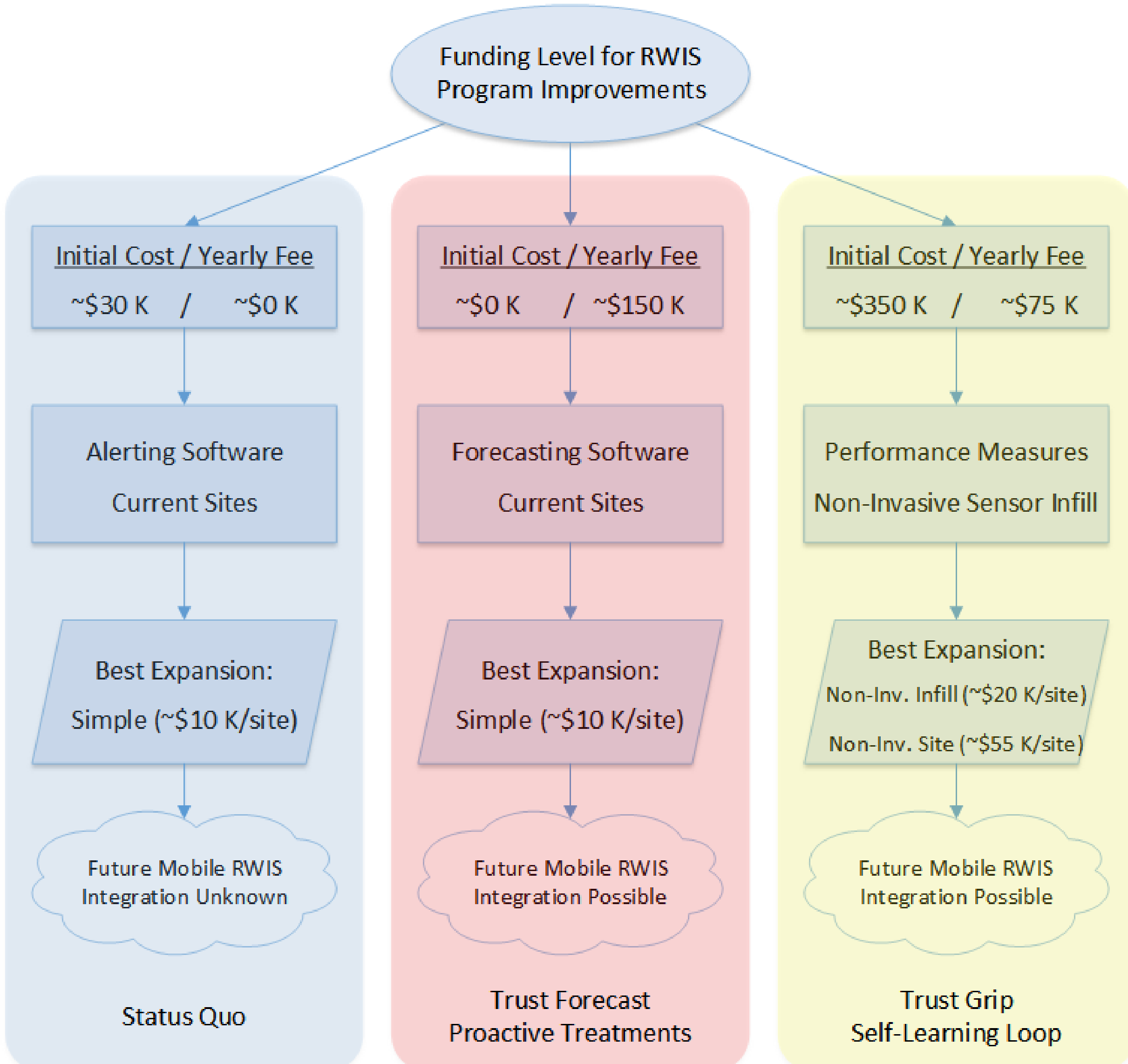


Figure 58: RWIS Program Improvements and Paradigms

If funding levels are relatively low for the foreseeable future, then substantial benefits may still be realized through modest investment in alerting capable software. Realizing the benefits of the change to alerting software requires little or no change to overall winter maintenance practices. If a more substantial investment in RWIS improvements can be made, then two possible directions may provide greater benefits, namely, obtaining a software service with advanced forecasting and treatment recommendations or obtaining a software service with automated performance metrics. These two more costly directions may be the most beneficial overall, but would require changes to winter maintenance practices.

High quality advanced weather forecasts have been shown to reduce overall labor and material costs (Ye, et. al., 2009a; Strong & Shi, 2008; Shi, 2015). The amount of savings realized from better forecasts is dependent on the accuracy and use of the forecasts (Ye, et. al., 2009b). For these reasons this direction may represent a change in overall winter maintenance practices, as the benefits of this options would depend on: 1) the forecast provider significantly exceeding the accuracy of free forecast options, 2) maintenance personnel trusting the forecast information, and 3) maintenance personnel using the forecast information for more timely and proactive treatment (i.e. more efficient scheduling, increased anti-icing treatments).

While only being extensively used in one state to date, automated performance measures have been found to reduce overall material costs and improve road conditions (Koeberlein, et. al., 2015; Koeberlein, 2015). Using automated performance measures requires the use of non-invasive road weather sensors at RWIS sites, so some level of retro-fitting existing RWIS sites with these sensors would be required for this approach. This option also represents a change in overall winter maintenance practices as winter maintenance personnel would have to: 1) trust the grip readings and winter performance measures and that they accurately represent road conditions, 2) monitor how effective their chosen treatments are on grip level and the winter performance measures, and 3) improve their effectiveness through a self-learning loop type process choosing more successful treatments having been able to see their past treatment-to-grip outcomes.

At this time the extensive use of mobile RWIS is not desired or recommended for Montana given the current state of its use and the quantified benefits related to its use considered in this project. Mobile RWIS use could be beneficial in the future as applications of the technology mature.

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APPENDIX A: STATE OF PRACTICE SURVEY

The objective of this survey is to understand the state of practice related to Road Weather Information Systems (RWIS) including the uses of RWIS data and the planning and management of RWIS programs in transportation agencies. This survey should be completed by those in your agency who are familiar with RWIS use, management, and planning. Participation is voluntary, you can choose not to answer any question that you do not want to answer, and you can stop at any time. The survey has 15 questions in total and is expected to take approximately 15 minutes. Thank you in advance for your participation.

1. Please enter your contact information: (We may wish to contact you if we need clarification or desire more information regarding a response)

Name	
Title	
Agency	
Phone	
Email	

2. What are the primary and secondary uses for RWIS data in your state/province? (Enter 1 for primary use, enter 2 for secondary use, enter 0 for not used)

Winter Maintenance (e.g. snow and ice pre-treatment and removal)

Traveler Information

Manual weather warnings posted to static or dynamic message signs (DMS)

Weather-responsive intelligent transportation system (ITS) applications (e.g. DMS warnings automated by weather sensors)

Share data with non-agency weather service providers (e.g. National Weather Service)

Weather related performance metrics (e.g. time to bare pavement, time to normal traffic conditions)

Aeronautics (e.g. flight planning, storm monitoring/forecasting)

[ ] Others: [ ]

3. Do you also collect operational data (i.e. traffic speed, traffic volume, vehicle class, vehicle weight) at RWIS sites?

- ( ) Yes, at most (75% to 100% of) RWIS sites
- ( ) Yes, at many (25% to 75% of) RWIS sites
- ( ) Yes, but only at some (1% to 24% of) RWIS sites
- ( ) No, we do not collect operational data at RWIS sites

4. Do you use any mobile RWIS (weather sensors and/or cameras mounted to vehicles to monitor weather conditions in real-time)?

- ( ) Yes, as a non-trivial part of our RWIS program
- ( ) Yes, but only as a very limited or experimental portion our RWIS program
- ( ) No, we do not use any mobile RWIS

5. What percent of your **current** funding / efforts go toward mobile RWIS vs. traditional stationary RWIS?

- ( ) zero mobile / 100% stationary
- ( ) low (1%-10%) mobile / 90%-99% stationary
- (•) moderate (11%-50%) mobile / 50%-89% stationary
- ( ) high (50%-100%) mobile / 0%-50% stationary
- ( ) don't know

6. What percentage of your **future** funding / efforts will likely go toward mobile RWIS vs. traditional stationary RWIS **5 years** from now?

- ( ) zero mobile / 100% stationary
- ( ) low (1%-10%) mobile / 90%-99% stationary
- ( ) moderate (11%-50%) mobile / 50%-89% stationary
- ( ) high (50%-100%) mobile / 0%-50% stationary
- ( ) don't know

7. Do you incorporate mobile maintenance vehicle data into RWIS (e.g. plow data, spreader data, Canbus data)?

- Yes, extensively
- Some, and we are making efforts to do more of this
- Some, but we are not making efforts to do more of this
- No, we collect mobile maintenance vehicle data but do not incorporate that into RWIS
- No, we do not collect mobile maintenance vehicle data

8. How have RWIS locations typically been chosen in your agency? (select all that apply)

- DOT Maintenance personnel knowledge for extreme weather locations
- DOT Maintenance personnel knowledge for a comprehensive grid type coverage
- Geo-Spatial analysis considering winter crash history
- Geo-Spatial analysis considering climate history
- Geo-Spatial analysis considering traffic volumes and/or road class
- Public Input
- DOT Traveler Information Staff Input
- DOT Operations Staff Input
- Others

9. Please rank the weather attributes for your uses as one of the following: not necessary, helpful, or must have.

	Not Necessary	Helpful	Must Have
air temperature			
humidity			
barometric pressure			

	Not Necessary	Helpful	Must Have
solar radiation			
visibility			
wind speed & direction			
precipitation occurrence			
precipitation type			
precipitation intensity / depth			
pavement temperature			
pavement condition (dry, wet, ice, etc.)			
chemical presence			
chemical concentration			
freeze temperature			
friction			
static camera image			
live video			

10. Open architecture, non-proprietary controllers and communications are:

- Required for our RWIS program
- Desired for our RWIS program
- Not desired for our RWIS program
- No preference for open vs. proprietary controllers and communication

11. Forecasts provided by RWIS vendors to your agency are:

- Very accurate and relied upon more than other sources
- Somewhat accurate and taken into consideration along with other sources
- Somewhat questionable and often ignored in favor of other sources
- Very questionable and other sources are therefore exclusively used
- Vendor forecast are not provided to our agency

12. Currently our agency is: (select all that apply)

- Expanding the geographic coverage of RWIS in our state/providence by adding more RWIS sites
- Adding additional sensors to existing locations for more and/or improved information
- Adding mobile RWIS to increase coverage and/or capabilities
- Focused on maintaining current RWIS configuration as it is deemed adequate for current needs
- Other:

13. Balancing costs associated with RWIS sites can depend on many factors, but one aspect is the type and number of sensors at each RWIS site. It has been suggested that certain agency needs may potentially be met with a limited installation (e.g. only a camera and pavement temperature sensor at each RWIS site).

If you were tasked with creating an RWIS program for your agency from scratch (given today's technology and your current knowledge) it would: (select all that apply)

- Have many more sites with mostly cameras only (made possible by the cost savings per site)
- Have somewhat more locations with cameras and pavement temp. sensors (made possible by cost saving per site)
- Have more sensors, but fewer locations (fewer locations as feasible with more costly equipment per site)
- Have a similar number of sites as it does now, with similar number of sensors

☐ Utilize mobile RWIS exclusively

☐ Other:

14. What software do you use to display RWIS data? (e.g. Vaisala Road Weather Navigator, SSI SCAN Web, High Sierra Electronics DataWise, agency developed application)

15. Who operates and maintains your RWIS software? (e.g. Lufft, Vaisala, agency personnel)

16. Who operates and maintains your RWIS hardware? (e.g. Lufft, Vaisala, agency personnel)

17. Are there ways in which you would like to improve upon your current RWIS software? If yes, please describe. (e.g. it would be better if each station showed a graph of the past 2 days readings, it would be better if it was easier to view on mobile devices, etc.)

18. Has your agency determined benefit/cost relationships for your RWIS program? If yes, please describe or link to website/report or ask us to contact you for more details if possible.

19. Are there any aspects of your current RWIS program that you would like to see improved to better meet your needs? (resources, budget, software, hardware, vendors, mobile capabilities, etc.)

20. What is the future of your current RWIS program? (status quo, additional sites, integration with ITS or travel information, adding mobile, adding traffic data, removal, etc.)

21. Please add any other information or comments that you feel may be related and/or useful. You may also contact the research team at:

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aalkaisy@ce.montana.edu

(406)-994-6116

Survey Powered By Qualtrics

APPENDIX B: NEEDS ASSESSMENT QUESTIONNAIRE

Maintenance Personnel Needs Assessment Questionnaire

Responsibilities / Practices / Decision Making

- Are your primary concerns snow and ice pretreatment and removal?
- Do you have responsibilities outside of winter maintenance that utilize road weather information system (RWIS) data (i.e. spring thaw load restrictions, others)?
- Do you have winter maintenance mission statement, goals, objectives?
- Do you use any winter maintenance performance metrics to evaluate performance (ie. time to bare pavement, time to wet pavement, return to near-normal traffic, friction, travel speeds, etc)?
- What % of your winter maintenance decisions are driven by RWIS data (either directly or via forecasts using RWIS data) vs outside sources like TV weather forecasts, National Oceanic and Atmospheric Administration (NOAA) Weather Alerts, etc.?
- Are maintenance decision support systems (MDSS) commonly used, how much human involvement is necessary in MDSS guided decisions?

Equipment and Software

- Rank weather attributes for your uses as must have (1) OR helpful (2) OR not necessary (3)

air temp.	humidity	barometric pressure
solar radiation	visibility	wind speed and direction
precip. occurrence	precip. type	precip. intensity
precip. depth	pavement temp	pavement condition (dry, wet, ice, ...)
chemical presence	chemical concentration	freeze temp. (using chemical sensing)
friction	static camera image	live video

Others:

- What reporting frequency do you need for critical attributes?
- Are current sensors accurate and reliable?
- Past studies performed for other transportation agencies have found instances of different RWIS sensor types reporting inaccurate data that does not match personnel observations. Do these errors also occur in Montana?
- Do sensors fail often?
- Are RWIS communications reliable and timely?
- Do communications failures often hinder data transmission?
- Are sensor readings communicated frequently enough?
- Is the most common failure of: sensors OR communications OR power OR software?
- Past studies vary: some agencies want temperature sensors at depths underground some agencies don't need that – what about Montana?
- Past studies have shown desires for certain sensor capabilities – are the following also wanted in Montana:
  - better precipitation sensors (with type, intensity, depth)
  - visibility sensors
  - cameras (with PTZ and more frequent static images or live video)
  - non-invasive pavement sensors
- Currently are static images from RWIS cameras updated frequently enough?
- Is live video beneficial?
- Is vandalism of RWIS equipment a problem?
- Are mobile sensors desired? Do you see benefits to having a mobile sensor fleet?
- What does the ideal RWIS software display?
- Is the display of RWIS data on mobile devices and smartphones needed?

Maintenance of RWIS Equipment and Software

- Who installs your environmental sensor station (ESS) equipment?
- Who performs maintenance on your ESS equipment?
- Who performs maintenance on your RWIS software?
- Would a performance based service contract be beneficial (ie. pay a vendor to maintain and deliver specified quality of accurate and reliable RWIS data)?

Geographic Coverage and Placement

- Some past studies have indicated that winter maintenance needs could potentially be met by very limited ESS deployments using only a camera and pavement temp sensor? Is that possible for your needs in Montana?
- Please discuss your desired balance between: more numerous but limited sensor ESS sites vs. fewer but more comprehensive ESS sites?
- Are any ESS placements currently the result of other uses besides winter maintenance?
- Are any additional sensors at existing ESS specifically for uses other than winter maintenance?

Other / Overall / I wish…

- If cost were no issue, what would be best for you?
- I think we need: more ESS locations OR more sensors at existing ESS locations OR better sensors/communications/power at existing locations?
- Suggested other groups or people to interview?

Any last thoughts on what to improve and/or how to improve it?

APPENDIX C: BENEFIT COST QUANTITY DETAILS

Crash Reductions

Table 21 shows the crash costs for different crash types as defined by the American Association of State Highway and Transportation Officials (AASHTO) in the Highway Safety Manual (HSM). Costs are adjusted to represent 2016 dollars using US Bureau of Labor Statistics Consumer Price Index and Employment Cost Index methods as suggested in the HSM.

Table 21: Crash Costs (rounded to nearest thousand)

Crash Type	HSM Cost
PDO	$10,000
Injury C	$62,000
Injury B	$111,000
Injury A	$303,000
Fatal	$5,712,000

Using methods from McKeever et al. (1998) with updated crash costs, RWIS presence results in approximately ***10%*** more time with road conditions wet as opposed to icy/snowy during storm events. This results in a crash reduction savings of ***$0.0618*** per VMT. This saving rate can then be used with a storm effected VMT amount to find crash dollars saved for adding RWIS where none was previously present. Half of this rate will be used for “fair” to “good” RWIS coverage improvements.

Using methods from McKeever et al. (1998) with updated crash costs and findings from another study (Blackburn et al., 1994[5]), proactive anti-icing compared to conventional deicing results in approximately ***20%*** more time with road conditions wet as opposed to icy/snowy during storm events. This results in a crash reduction savings of ***$0.1236*** per VMT. This saving rate can then be used with a storm effected VMT amount to find crash dollars saved.

Using methods from another study (Hanbali, 1994[6]), winter maintenance activities compared to performing no winter maintenance activities results in an approximate crash reduction savings of ***$1.1665*** per VMT. This saving rate can then be used with a storm effected VMT amount to find crash dollars saved.

[5] Blackburn, R., McGrane, E., Chappelow, C., and Harwood, D. “Development of Anti-Icing Technology.” Strategic Highway Safety Program Report SHRP-H-385. 1994.

[6] Hanbali, R. “Economic Impact of Winter Road Maintenance on Road Users.” *Transportation Research Record: Journal of the Transportation Research Board*. No 1442. 1994.

Storm Events and Effected Crew

Using only state owned roads and most recently available data, Montana experiences approximately ***9,496*** MVMT per year[7].

Using NOAA database records over the past ten available winter seasons (2005-2006 through 2014-2015), Montana has experienced an average of ***57.9*** days per year with a winter related storm event be it a blizzard, freezing fog, heavy snow, ice storm, winter storm, or winter weather[8]. To be conservative it is assumed that each storm day corresponds to a single event per day. These winter events effect an average of ***5.5*** counties per event-day, which is equivalent to approximately ***11.6*** maintenance sections affected per event-day.

Assuming an average winter related storm event lasts ***6*** hours, the average yearly winter storm effected VMT is then approximately 37.02 MVMT for the state. Further adjusting this VMT for the fact that traffic levels in the winter months (October through March) are lower than the yearly average traffic[9] yields an adjusted yearly winter storm effected VMT is then approximately ***30.92*** MVMT for the state.

There are total winter 709 maintenance crew in 118 maintenance sections which results in approximately ***6*** potentially effected winter maintenance crew per storm effected maintenance section.

Travel Delay Reductions

The average speed reduction for arterials is approximately ***35%*** for snowy or slushy pavement[10].

The cost of time for a passenger car with 1.25 average occupancy is ***$22.09*** per hour and cost of time for commercial vehicle is ***$94.04*** per hour[11].

Assuming passenger cars have an overall average speed of 70 mph in normal conditions and commercial vehicles have an average overall speed of 60 mph in normal conditions and using an average of 25% speed reduction (35% for snow - 10% for wet) leads to delay costs for snowy roads compared to wet roads of ***$0.1052*** per VMT for passenger cars and ***$0.5224*** per VMT for commercial vehicles.

Using National VMT values published by the USDOT Bureau of Transportation Statistics commercial vehicles may be approximately 10% of the total highways VMT[12]. This can then be used to calculate an overall delay cost for snowy roads compared to wet roads of ***$0.1469*** per

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[7] Traffic Data. Montana Department of Transportation. http://www.mdt.mt.gov/publications/datastats/traffic_maps.shtml accessed April 25, 2016.

[8] Storm Events Database. NOAA - National Centers for Environmental Information. http://www.ncdc.noaa.gov/stormevents/ accessed April 25, 2016.

[9] Montana's Estimated Monthly Vehicle Miles Traveled. MDT. http://www.mdt.mt.gov/other/webdata/external/Planning/traffic_reports/mvmt_table.pdf Accessed May 31, 2016.

[10] “Snow and Ice” FHWA Road Weather Management Program. http://www.ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm Accessed April 21, 2016

[11] Schrank, D., Eisele, B., Lomax, T., and Bak, J. “2015 Urban Mobility Scorecard.” Texas A&M Transportation Institute and INRIX, 2015.

[12] “Table 1-35: U.S. Vehicle-Miles” USDOT-RITA-BTS. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_35.html accessed April 21, 2016

VMT. This value can be used for the cost savings per winter maintenance treated VMT with the understanding that winter maintenance treatments produce an approximate effect of snowy/icy roads to wet/bare roads.

Using methods proposed by McKeever et al. (1998) that RWIS presence leads to a 10% increase in time the roads are wet instead of icy/snowy: the delay cost savings of RWIS presence alone is then ***$0.0147*** per VMT. Half of this rate will be used for “fair” to “good” RWIS coverage improvements.

Using the findings of another study by Blackburn et al. (1994) that proactive anti-icing leads to a 20% increase in time the roads are wet instead of icy/snowy: the delay cost savings of using proactive inti-icing compared to traditional deicing and snow removal is then ***$0.0294*** per VMT.

Winter Maintenance Costs

MDT total yearly winter maintenance costs are approximately $43.48M for 2016[13].

Typically about 40% of winter maintenance costs are for labor, 30% are for equipment, and 25% are for materials (Boon & Cluett, 2002[14]).

These proportions result in approximate total labor costs of ***$17.39M*** and materials costs of ***$10.87M***.

Idaho Experience

The percent of time that mobility was not significantly impeded (as monitored by automated performance measures using non-invasive sensors that utilize grip level readings and normalized by storm severity) in Idaho improved from the baseline season of 28% to the most recently report 3-year average of 62% (Koeberlein, 2015). This 34% improvement in the time mobility is not impeded is analogous to the time grip levels remain high during winter storms.

Using this 34% improvement with crash cost reduction methods in Appendix A yields an approximate crash reduction savings of ***$0.2101*** per applicable VMT for utilizing non-invasive sensors and automated performance measures.

Similarly, using this 34% improvement with delay cost reductions in Appendix C yields an approximate delay reduction savings of ***$0.0499*** per applicable VMT for utilizing non-invasive sensors and automated performance measures.

Idaho has also reported significant winter maintenance cost reductions as a result of their RWIS program (Koeberlein, 2015). Specifically, a 40% materials savings has been documented (ITD, 2009[15]). A conservative estimate of ***20%*** materials savings is used for applicable scenarios.

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[13] “About MDT” Montana Department of Transportation. http://www.mdt.mt.gov/mdt/docs/about-mdt.pdf Accessed April 21, 2016.
[14] Boon, C. and Cluett, C. “Road Weather Information Systems: Enabling Proactive Maintenance Practices in Washington State.” Report WA-RD 529.1 for Washington State Department of Transportation. 2002.
[15] Idaho Transportation Department. “How Idaho’s non-invasive RWIS network is paying for itself while helping to set new standards for improved service and operations.” ITD Transporter, January 30, 2009.

<u>Mobile RWIS Coverage</u>

During every 30 minute period:

Fixed RWIS Site:

- 25 mile coverage radius (*in accordance with prior literature review findings*)
- 30 minute weather observation frequency (*current MDT polling-reporting practice*)

Mobile RWIS:

- A mobile RWIS measurement has the same geographic coverage as a fixed site (*assumed*)
- 50 mph average vehicle speed (*assumed*)

Then a mobile RWIS would have approximately ***1.5 times*** the geographic coverage of a fixed RWIS (for a linear roadway negating coverage perpendicular to road) as shown in Figure 59.

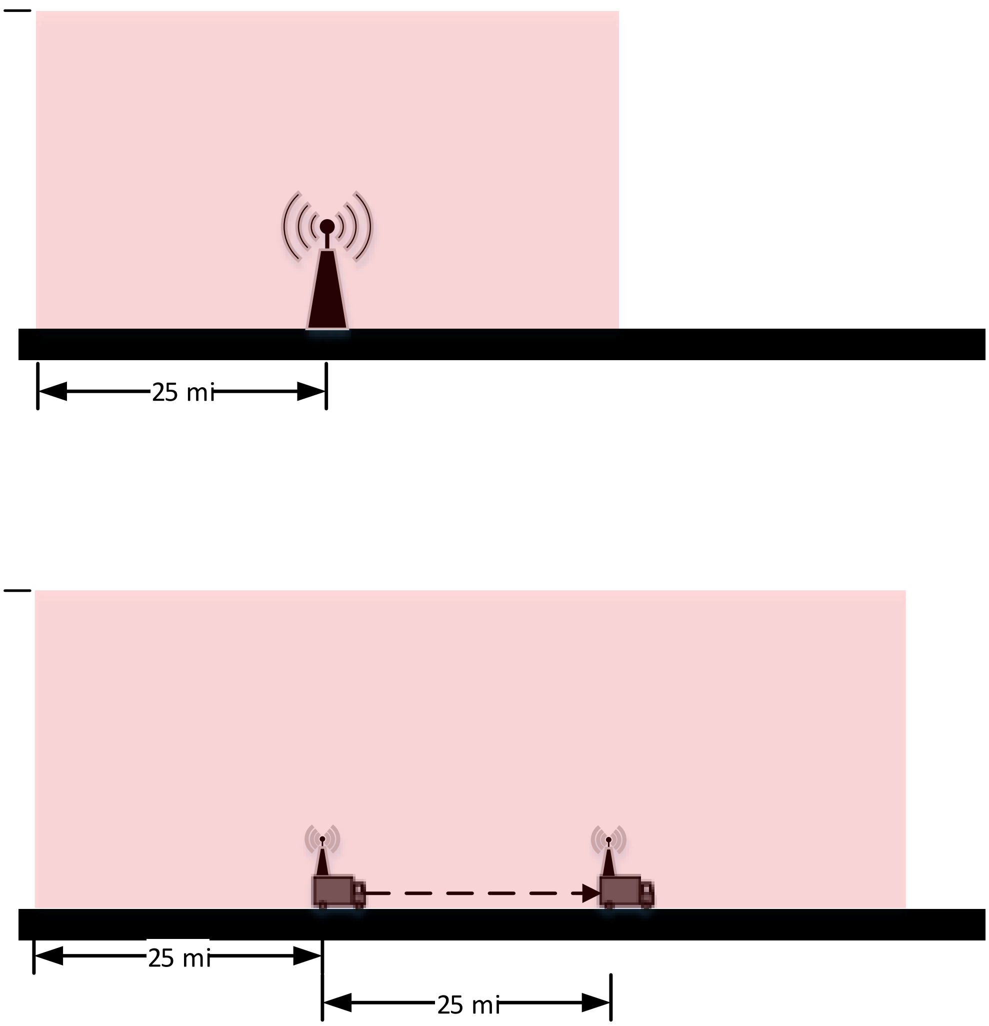

Figure 59: Geographic Coverage of Fixed (top) and Mobile (bottom) RWIS

APPENDIX D: SITE PRIORITIZATION SAMPLE CALCULATIONS

$OM_{site\#2} = w_1\,(WI) + w_2\,(CI) + w_3\,(TI) + w_4\,(GC) + w_5\,(OF)$

$w_1 = w_2 = w_3 = w_4 = w_5 = 0.2$ (*assumed*)

$WI = a_1\,(FT) + a_2\,(RF) + a_3\,(SI) + a_4\,(TG) + a_5\,(SG)$

$a_1 = a_2 = a_3 = a_4 = a_5 = 0.2$ (*assumed*)

FT = (number months with mean min. temp. below freezing[16])/12

FT = 7/12 = *0.5833*

RF = score from Table 12 (using total annual rainfall[17])

RF = *0.4* (mean annual rainfall 11.58 inches)

SI = score from Table 12 (using mean snowfall per month[18] for months more than 2")

SI = *0.5* (mean 8.6" snow per month for moths with more than 2")

TG = score from Table 12 (using mean temperature[1] gradient for nearby sites)

TG = *0.2* (0.12 degree/mile gradient using 3 nearby stations)

SG = score from Table 12 (using mean annual snowfall[3] gradient for nearby sites)

SG = *0.3* (2.37 inch/mile gradient using 3 nearby stations)

WI = 0.2 (*0.5833*) + 0.2 (*0.4*) + 0.2 (*0.5*) + 0.2 (*0.2*) + 0.2 (*0.3*) = ***0.397***

CI = from Table 16 (using CI_{adj})

CI_{adj} = MAX [(CR), (CR) * (1+ (PW-0.15))]

CR = crash rate (using EPDO crashes per MVMT[19])

CR = 39.24

PW = percentage of weather related crash for 20 miles around site

PW = 0.13

CI_{adj} = MAX [39.24, (39.24)*(0.98)] = 39.24

CI = ***0.4***

TI = from Table 15 (using total traffic[20] on all highways segments within 30 miles)

TI = ***1.0*** (455 MVMT on all highways within 30 miles)

GC = from Table 17 (using nearby weather station coverage[21])

GC = ***0.4*** (643 sq. mi per station)

OF = from Table 18 (using power and communications availability)

OF = ***1.0*** (*assumed*)

$OM_{site\#2}$ = 0.2 (***0.397***) + 0.2 (***0.4***) + 0.2 (***1.0***) + 0.2 (***0.4***) + 0.2 (***1.0***) = ***<u>0.6394</u>***

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[16] 30 year mean (1981-2010) from Montana Climate Office http://climate.umt.edu/atlas/temperature/default.php
[17] 30 year mean (1981-2010) from Montana Climate Office http://climate.umt.edu/atlas/precipitation/default.php
[18] GIS Contour Map developed using 30 year mean (1981-2010) data from National Climate Data Center www.ncdc.noaa.gov
[19] Crash rate for 20 miles centered at site with EPDO rates of 25 per fatal and 15 per injury crashes.
[20] Excludes local roads, traffic data from MDT: www.mdt.mt.gov/publications/datastats/traffic_maps.shtml
[21] Weather station coverage (30mi x 30mi grid as shown in Figure 56), non-RWIS stations count as 0.7 stations.

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