ILLINOIS CENTER FOR TRANSPORTATION

CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 22-004
UILU-ENG-2022-2004
ISSN: 0197-9191

Evaluating the Benefits of Implementing Mobile Road Weather Information Sensors

Prepared By
Khaled El-Rayes
Ernest-John Ignacio
University of Illinois Urbana-Champaign

Research Report No. FHWA-ICT-22-004

A report of the findings of

ICT PROJECT R27-SP47
Evaluating the Benefits of Implementing Mobile Road Weather Information Sensors

https://doi.org/10.36501/0197-9191/22-004

Illinois Center for Transportation

February 2022

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-ICT-22-004	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Evaluating the Benefits of Implementing Mobile Road Weather Information Sensors		**5. Report Date** February 2022 **6. Performing Organization Code** N/A
7. Authors Khaled El-Rayes and Ernest-John Ignacio (https://orcid.org/0000-0002-9916-953X)		**8. Performing Organization Report No.** ICT-22-004 UILU-2022-2004
9. Performing Organization Name and Address Illinois Center for Transportation Department of Civil and Environmental Engineering University of Illinois at Urbana-Champaign 205 North Mathews Avenue, MC-250 Urbana, IL 61801		**10. Work Unit No.** N/A **11. Contract or Grant No.** R27-SP47
12. Sponsoring Agency Name and Address Illinois Department of Transportation (SPR) Bureau of Research 126 East Ash Street Springfield, IL 62704		**13. Type of Report and Period Covered** Final Report 4/16/21–2/28/22 **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. https://doi.org/10.36501/0197-9191/22-004		

16. Abstract

State departments of transportation (DOTs) have traditionally utilized fixed road weather information sensors (RWIS) to improve road safety during inclement weather; enhance the management of labor, equipment, and materials for winter road maintenance; and reduce adverse environmental impacts from road maintenance activities. Despite the benefits of these fixed RWIS sites, their coverage and effectiveness are limited because of their stationary locations. To overcome these limitations, recent advances in mobile road weather information sensing technology and cellular communications have enabled the development of mobile RWIS that can be deployed on vehicles to expand the limited coverage of fixed RWIS networks. Combining mobile RWIS, fixed RWIS networks, automatic vehicle location, and maintenance decision support systems (MDSS) provide DOTs with accurate georeferenced road and weather information that can be used by DOTs to optimize winter road maintenance operations and deicer applications. This report presents the findings of a research project funded by the Illinois Department of Transportation to investigate the effectiveness of mobile RWIS and MDSS in improving winter maintenance operations. This project had the following three objectives. First, conduct a literature review to gather and analyze current practices and latest research studies on mobile RWIS and their use for collecting real-time winter roadway conditions to optimize winter maintenance operations. Second, perform interviews with other state DOTs to gather and analyze their experiences and best management practices for the deployment and use of mobile RWIS and MDSS. Third, develop recommendations for a pilot study to evaluate the deployment and performance of mobile RWIS and MDSS in order to determine their effectiveness, implementation requirements, software/technology needs, operational challenges, and life-cycle costs.

17. Key Words Road Weather Information Sensors, Mobile Road Weather Information Sensors, Winter Maintenance, Maintenance Decision Support System		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 62 + appendix	**22. Price** N/A

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-SP47: Evaluating the Benefits of Implementing Mobile Road Weather Information Sensors**. ICT-R27-SP47 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review Panel (TRP) were the following:

- Laura Shanley, TRP Chair, Illinois Department of Transportation
- Joshua Butterfield, Illinois Department of Transportation
- Clint Faugust, Illinois Department of Transportation
- Brian Galloway, Illinois Department of Transportation
- Kurt Kinion, Hoosier Company
- Dean Mentjes, Federal Highway Administration
- Dave Rennels, Illinois Department of Transportation
- Dave Speicher, Illinois Department of Transportation
- Megan Swanson, Illinois Department of Transportation
- Trisha Thompson, Illinois Department of Transportation
- Bill Turczyn, Illinois Department of Transportation

EXECUTIVE SUMMARY

State departments of transportation (DOTs) have traditionally utilized fixed road weather information sensors (RWIS) to improve road safety during inclement weather; enhance the management of labor, equipment, and materials for winter road maintenance; and reduce adverse environmental impacts from road maintenance activities. Despite the benefits of these fixed RWIS sites, their coverage and effectiveness are limited because of their stationary locations. To overcome these limitations, recent advances in mobile road weather information sensing technology and cellular communications have enabled the development of mobile RWIS that can be deployed on vehicles to expand the limited coverage of fixed RWIS networks. Combining mobile RWIS, fixed RWIS networks, automatic vehicle location (AVL), and maintenance decision support systems (MDSS) can provide DOTs with accurate georeferenced road and weather information that can be used to optimize winter road maintenance operations and deicer applications. To investigate the effectiveness of mobile RWIS and MDSS in improving winter maintenance operations, a research project funded by the Illinois Department of Transportation was conducted. This report presents the findings of this research project. The objectives of this project were as follows:

- Conduct a literature review to gather and analyze current practices and latest research studies on mobile RWIS and their use for collecting real-time winter roadway conditions to optimize winter maintenance operations. The conducted literature review focused on relevant federal guidelines and programs, utilization of mobile RWIS by state DOTs, performance of mobile RWIS, and commercially available mobile RWIS. One of the key findings of this literature review was the reported cost savings by several DOTs that were achieved by deploying mobile RWIS and MDSS during winter maintenance operations. For example, Indiana DOT reported that the use of mobile RWIS and MDSS in 2009 enabled it to achieve annual cost savings of $10,957,672, which includes material savings (salt/brine) of $9,978,536 and labor savings of $979,136.

- Perform interviews with four state DOTs (Colorado, Indiana, Michigan, and Minnesota) to gather and analyze their experiences and best management practices for the deployment and use of mobile RWIS and MDSS. The interviews covered the following topics related to state DOTs' use of mobile RWIS and MDSS: (1) deployment and use; (2) software and communications; (3) experienced costs and savings; (4) encountered installation and operational challenges; (5) required maintenance; (6) collected data use, storage, and retention; and (7) additional feedback and comments. One of the key findings of these interviews were the reported cost savings experienced by several state DOTs. For example, Minnesota DOT reported that the use of mobile RWIS and MDSS in 11 winter events in 2010 enabled it to achieve an average of 53% reduction in salt usage and cost savings of $2,308,866.

- Develop recommendations for a pilot study to evaluate the deployment and performance of mobile RWIS and MDSS in order to determine their effectiveness, implementation requirements, software/technology needs, operational challenges, and life-cycle costs. The proposed research objectives of this pilot study are as follows: (1) identify potential districts,

routes, vehicles, and personnel that will participate in the pilot study; (2) install mobile RWIS units and MDSS display units on selected plows and supervisor vehicles; (3) conduct the first phase of the pilot study to evaluate the effectiveness of currently utilized and the newly purchased mobile RWIS units and MDSS during the first winter season; (4) conduct the second phase of the pilot study to evaluate the effectiveness of deployed mobile RWIS and MDSS during the second winter season; (5) analyze the effectiveness of all tested mobile RWIS units and MDSS in improving winter maintenance operations on Illinois roads; and (6) develop recommendations for future deployment of mobile RWIS and MDSS throughout Illinois.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

PROBLEM STATEMENT

State departments of transportation (DOTs) have traditionally utilized fixed road weather information sensors (RWIS) to improve road safety during inclement weather; enhance the management of labor, equipment, and materials for winter road maintenance; and reduce adverse environmental impacts from road maintenance activities (ITS 2017). To accomplish this, fixed RWIS are used to measure (1) atmospheric data, including temperature, humidity, visibility distance, wind speed and direction, precipitation type and rate, and (2) pavement data, including surface temperature, condition (e.g., wet, icy, flooded), and subsurface temperature (FHWA 2020a). Despite the benefits of these fixed RWIS sites, their coverage and effectiveness are limited because of their stationary locations. Recent advances in mobile road weather information sensing technology, and cellular communications have enabled the development of mobile RWIS that can be fixed to vehicles (MassDOT 2016). Mobile RWIS equipment can be utilized to fill in weather information gaps and supplement established fixed RWIS networks. The data collected by mobile RWIS allows transportation agencies to make decisions for specific roadways with higher precision and accuracy than traditional fixed RWIS data (MnDOT 2019). Mobile RWIS are often utilized with automatic vehicle location (AVL), a vehicle-tracking system similar to GPS that assists public agencies in tracking their maintenance fleet. In addition to mobile RWIS and AVL, state DOTs often utilize mobile data collection (MDC) sensors on winter maintenance vehicles to measure deicing material application rate, type, and plow position. Combining mobile RWIS, AVL, and MDC provides DOTs with accurate georeferenced road condition and weather information, recent maintenance activities including material type and application rate (SDDOT 2009). This integrated real-time monitoring of road conditions, weather information, and maintenance vehicle activities can be used by DOTs to optimize winter road maintenance operations and deicer applications. Accordingly, there is a need for Illinois Department of Transportation (IDOT) to conduct an exploratory study that focuses on evaluating the effectiveness of commercially available mobile RWIS as well as gathering and analyzing the experiences of other state DOTs in collecting real-time winter roadway conditions using mobile RWIS and maintenance decision support systems (MDSS).

RESEARCH OBJECTIVES AND METHODOLOGY

The main goal of this research project was to evaluate the potential benefits of implementing mobile RWIS in Illinois to provide real-time winter roadway conditions and optimize deicing operations. To accomplish this goal, the research objectives of this project are as follows:

1) Conduct a literature review to gather and analyze the latest data on implementing and utilizing mobile RWIS.

2) Conduct interviews with state DOTs to gather their best management practices for implementing and utilizing mobile RWIS including, but not limited to, sensor selection, route selection, mounting, software and communications, findings, and lessons learned.

3) Develop recommendations for a pilot study to evaluate the deployment and performance of mobile RWIS and MDSS in order to determine their effectiveness, implementation requirements, software/technology needs, operational challenges, and life-cycle costs.

Proposed Techniques and Methodology

The research team accomplished the project objectives by adopting a rigorous research methodology. The methodology breaks down the research work into three major tasks (see Figure 1) that are described in more detail in the following chapters and appendix.

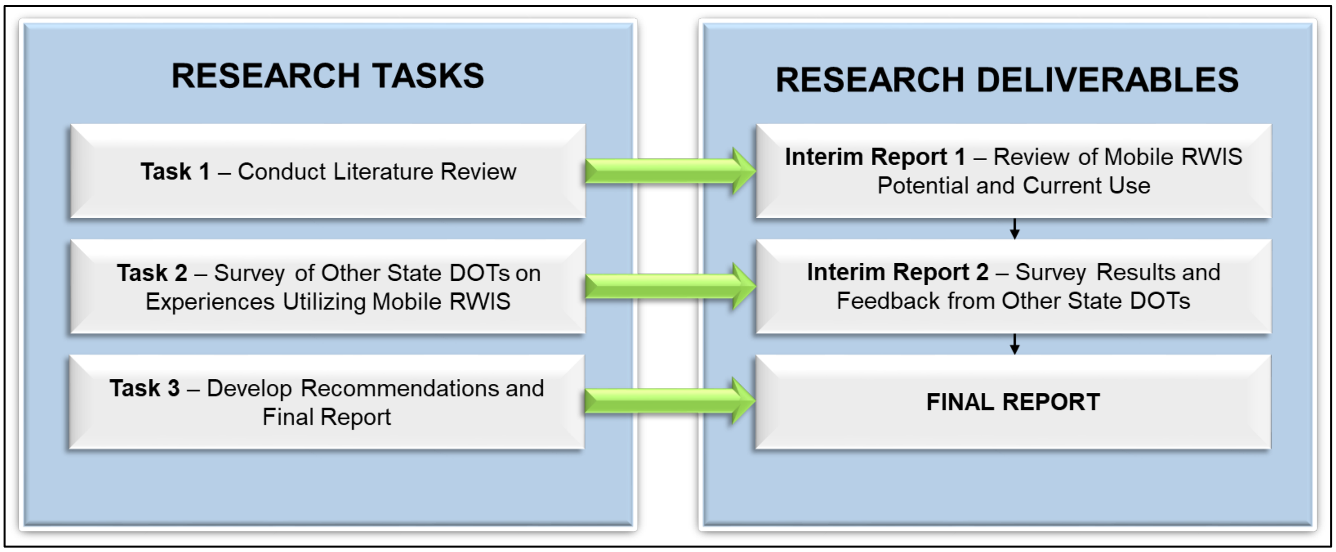


Figure 1. Diagram. Research tasks and deliverables.

CHAPTER 2: LITERATURE REVIEW

This chapter presents the findings of a literature review that was conducted to gather and analyze current practices and latest research studies on mobile RWIS and their use for collecting real-time winter roadway conditions to optimize winter maintenance operations. This literature review focuses on (1) relevant federal guidelines and programs as well as utilization of mobile RWIS by state DOTs, (2) performance of mobile RWIS, and (3) commercially available mobile RWIS. The literature review's findings of these three areas are presented in the following sections.

UTILIZATION OF MOBILE ROAD WEATHER INFORMATION SENSORS

This section highlights the main findings of the conducted literature review on (1) related federal guidelines and programs for collecting and utilizing mobile RWIS data, (2) the use of mobile RWIS by state DOTs, and (3) a recent survey of state DOTs on their use of mobile RWIS.

Related Federal Guidelines and Programs

This subsection summarizes the findings of the literature review on (a) federal guidelines for the deployment of weather data collection vehicles and their data communication with state DOT systems and (b) federal programs and MDSS for collecting road condition and weather data to provide recommendations on winter road maintenance.

Guidelines for Deploying Weather Data Collection Vehicles

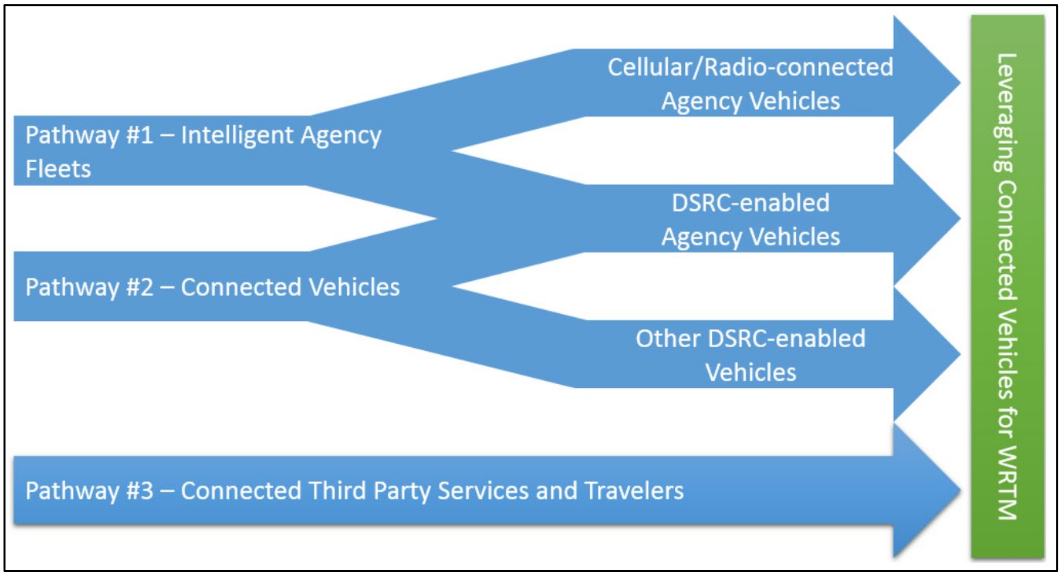
In 2016, the Federal Highway Administration (FHWA) developed the *Guidelines for Deploying Connected Vehicle-Enabled Weather Responsive Traffic Management (CV-WRTM) Strategies* to provide state and local DOTs with effective traffic management and operations strategies to mitigate roadway safety and mobility problems due to adverse weather. These guidelines provide strategies for the collection and integration of traffic, weather, and road condition data that can be used to serve multiple purposes, including winter maintenance operations, traveler information systems, and transportation asset management (FHWA 2016). These federal guidelines are often used by state DOTs to collect and integrate mobile RWIS weather and road condition data. These guidelines detail the planning, design, development, integration, and maintenance associated with CV-WRTM (FHWA 2016). The guidelines describe the three main "pathways" for implementing advanced WRTM:

- Pathway 1—Intelligent Agency Fleets: This pathway connects fleets of WRTM vehicles to state DOT systems using existing remote communication capabilities through either cellular links or agency-owned radio systems and can transmit both voice and data. The fleets include snowplows, highway patrol vehicles, and other maintenance vehicles that are frequent users of the roadway, especially during adverse weather conditions (FHWA 2016).

- Pathway 2—Connected Vehicles: This pathway requires vehicles to have dedicated short-range communication capabilities to communicate with state DOT systems. Dedicated short-range communication is a networking technology that allows for fast, secure, and reliable communications for various vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-nomadic-device applications (FHWA 2016).

- Pathway 3—Connected Third-Party Fleet Services and Travelers: This pathway utilizes private companies with fleets integrating high levels of connectivity to send and receive information to state DOT systems. The difference between Pathway 1 and Pathway 3 is the reliance on third-party providers to deliver and receive data from state DOT systems (FHWA 2016).

These three pathways are not mutually exclusive, and each pathway provides unique value to potential system deployments. Note that state DOTs and agencies can utilize their existing connected vehicles to identify the most effective pathway for their fleet, as shown in Figure 2 (FHWA 2016).



Note: DSRC = dedicated short-range communication. WRTM = weather-responsive traffic management.

Figure 2. Screenshot. Pathways for connected vehicle-enabled WRTM (FHWA 2016).

FHWA Pooled-Fund Study on Maintenance Decision Support Systems

FHWA initiated a program in 2001 to develop a winter road MDSS capable of using the collected road and weather data to provide recommendations on road maintenance and courses of action (NCAR 2021). The MDSS project is a pooled-fund study in collaboration with 19 state DOTs (see Figure 3) and 5 national laboratories to develop and implement a tool that can provide maintenance managers with precise surface condition forecasts and treatment recommendations for specific routes (FHWA 2006; TPFP 2017). MDSS have two interrelated functions: (1) to conduct a real-time assessment of current and future road and weather conditions and (2) to provide real-time winter maintenance treatment recommendations. First, MDSS assess the current road and weather conditions gathered by mobile and fixed RWIS along transportation routes in order to predict and portray how road conditions will change due to the forecast weather and the application of several candidate road maintenance treatments. Second, MDSS suggest optimal maintenance treatments that can be achieved within available staffing, equipment, and materials resources.

DOT officials that utilize MDSS reported their benefits in interviews conducted in 2007 (SDDOT 2009). The DOT officials reported that utilizing MDSS provides benefits to three groups: the state DOT, motorists, and society. State DOT benefits include enhancing the efficiency of winter maintenance operations and reducing their cost, reducing material use, optimizing scheduling/assignment of personnel, and improving decision making. Motorist benefits include enhanced safety and mobility for the travelling public, while societal benefits include reducing the use of snow and ice treatment materials and their negative impact on water quality, wildlife habitat, air quality, pavement integrity, and infrastructure corrosion. These benefits translate into a safer and more efficient transportation system (SDDOT 2009). The benefits can be further enhanced when combined with mobile RWIS, as described in the section titled "Developed Interview Questions." For example, some state DOTs have reported that mobile RWIS and MDSS precipitation forecasts were more accurate than traditional weather services because of their detailed interpretations of local weather data (FHWA 2010).

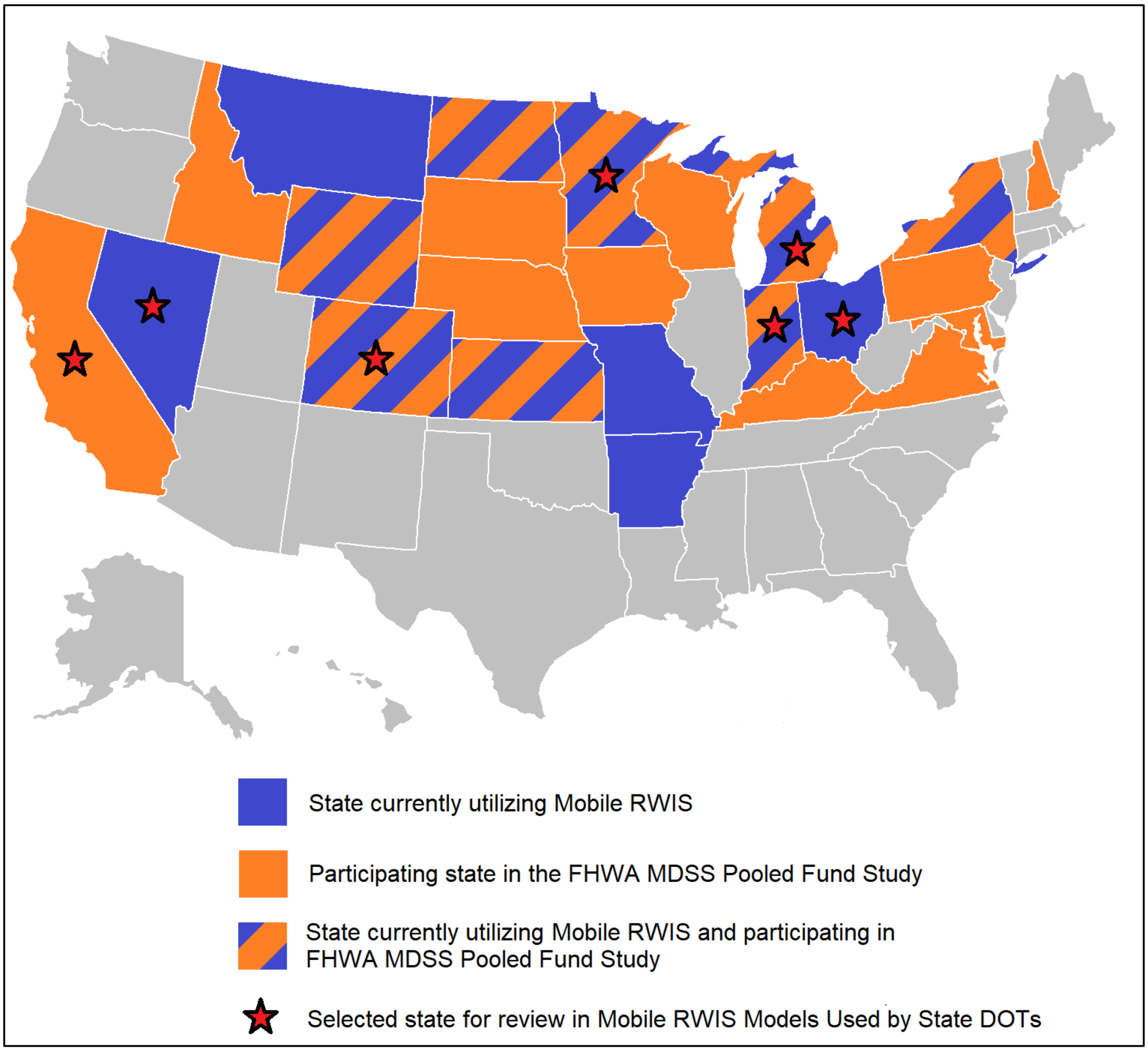


Figure 3. Diagram. States utilizing mobile RWIS and/or participating in MDSS pooled fund study.

The implementation challenges of MDSS were also reported by DOT officials in the interviews (SDDOT 2009). One of the main challenges reported by DOT officials was the "level of trust" that some decision makers have with the MDSS prescribed treatment. DOT officials reported that the level of trust and use of MDSS prescribed recommendations were expected to increase as the reliability of the MDSS recommended treatments continues to evolve and improve. For example, DOT officials reported that MDSS recommendations need to consider a range of factors that affect winter treatment operations such as the impact of high wind speeds on displacing dry treatments applied before or during storms (SDDOT 2009). A second challenge reported by DOT officials was the lack of confidence in MDSS performance and reliability due to insufficient data sources that are required by the MDSS. For example, states that have incomplete or inadequate fixed RWIS networks are less inclined to utilize MDSS. To overcome this challenge, mobile RWIS and other connected vehicle technologies have been deployed to supplement the insufficient data collected by fixed RWIS networks and provide the required level of data for MDSS (MnDOT 2019). Despite the implementation challenges of MDSS, DOT officials reported that MDSS have improved road safety, mobility, and cost savings (SDDOT 2009).

Utilization of Mobile RWIS by State DOTs

This section summarizes the findings of the literature review on the use of mobile RWIS by seven state DOTs. The DOTs were carefully selected to provide a comprehensive representation of states that have similar winter weather conditions to Illinois; diverse deployments of mobile RWIS, including year started, original fleet size, recent fleet size, and utilized RWIS models; and varying implementations of the aforementioned federal guidelines for data communication of weather data collection vehicles and participation in the FHWA MDSS pooled-fund study, as shown in Table 1. The selected seven states are Michigan, Minnesota, Indiana, Ohio, Colorado, Nevada, and California, as shown in Table 1 and Figure 3.

Michigan Department of Transportation

In 2013, the Michigan Department of Transportation (MDOT) started deploying mobile RWIS on 60 MDOT vehicles, including 40 light-duty cars (supervisor vehicles) and 20 winter maintenance trucks. MDOT reported they have expanded their fleet of mobile RWIS-equipped vehicles to 328 snowplows and 15 supervisor vehicles as of 2017 (MDOT 2016; AASHTO 2017). The mobile RWIS models used in MDOT vehicles include Vaisala Surface Pro (MDOT 2013, 2016). MDOT utilizes Pathways 1 and 2 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes cellular network, Wi-Fi, and dedicated short-range communications, as shown in Table 1 (MDOT 2016; AASHTO 2017).

The use of mobile RWIS started in 2013 when MDOT was sponsored by the USDOT / FHWA Road Weather Management Program to partner with the University of Michigan, Minnesota DOT, and Nevada DOT. The goal was to develop and deploy sensor technology on MDOT fleet vehicles that collect near real-time vehicle data to support winter weather MDSS (MDOT 2013). This initiative—the Integrated Mobile Observations (IMO) project—analyzed the feasibility and capability of a smartphone-based data-collection system to provide accurate and timely road condition data (MDOT 2016). The IMO project was conducted in three phases: developing and deploying sensor technology in a test fleet to collect near real-time vehicle data to support winter weather MDSS; continuing to improve the data-collection process to support weather-related analysts throughout the United States; and integrating additional relevant data sources, including fixed RWIS sites and road-side units (MDOT 2013, 2016, 2018a).

Table 1. Deployment of Mobile RWIS by Selected State DOTs

State DOT	Similar Winter Weather to Illinois	Year Started Using Mobile RWIS	Original Mobile RWIS Fleet Size	Recent Mobile RWIS Fleet Size (as of)	Mobile RWIS Models	Data Communication / Pathway	MDSS Used	References
Michigan	✓	2013	40 Snowplows 20 Supervisor Vehicles	328 Snowplows 15 Supervisor Vehicles (2017)	Vaisala Surface Patrol, Lufft MARWIS	Cellular Network, Wi-Fi, and Dedicated Short-Range Communications	✓	(MDOT 2016; AASHTO 2017)
Minnesota	✓	2013	329 Vehicles	590 Vehicles (2017)	Vaisala Surface Patrol, Lufft MARWIS, Teconer RCM411 & HSE IceSight	Cellular Network & Dedicated Short-Range Communications	✓	(MnDOT 2013; AASHTO 2017)
Indiana	✓	2006	10 Vehicles	130 Vehicles (2009)	Lufft MARWIS & Manual Driver Input	Dedicated Short-Range Communications	✓	(INDOT 2007; INDOT 2009)
Ohio	✓	2017	Initial Test Select Supervisor Vehicles	No Update Available	Lufft MARWIS	Cellular Network		(ODOT 2017)
Colorado	✓	2006	20 Snowplows	309 Snowplows (2015)	Vaisala Surface Patrol, Lufft MARWIS, Teconer RCM411 & HSE IceSight	Cellular Network	✓	(CDOT 2011; CDOT 2015)
Nevada		2009	10 Snowplows 10 Light Duty Vehicles	60 Vehicles (2017)	RoadWatch	Cellular Network & Dedicated Short-Range Communications	✓	(AASHTO 2017)
California		2005	2 Trucks 2 Snowplows	No Update Available	RoadWatch	Cellular Network	✓	(Caltrans 2006, 2015, 2019)

In the first phase (IMO 1.0), weather and road condition data-collection sensors were installed on a fleet of 60 MDOT vehicles, including 40 light-duty cars (supervisor vehicles) and 20 winter maintenance trucks. This weather and road condition data was gathered by a smartphone program called DataProbe that collects information from three sources within each vehicle. First, the smartphone provides date, time, latitude, longitude, altitude, number of satellites, speed, accelerometer data, and compass heading. Second, the vehicle's internal controlled area network provides information on the vehicle's air and coolant temperature, odometer, barometer, tachometer, speedometer, throttle, brakes, anti-lock braking system, electronic stability control, engine traction control, and braking traction control. Third, external mobile RWIS measure the road surface and air temperature, humidity, and dew point (MDOT 2016). This vehicle and external sensor data were gathered by cell phones via Bluetooth and transmitted to MDOT so that the agency can utilize real-time weather data to effectively manage winter maintenance operations (MDOT 2016).

The second phase (IMO 2.0) utilized the collected road and weather data to explore the feasibility and capability of using the smartphone-based data-collection system to generate road condition warnings for drivers via electronic road signs, website, and mobile phone applications. The real-time weather and road condition data collection and warning notification was displayed in a demonstration project at the 2014 Intelligent Transportation Systems (ITS) World Congress. The demonstration was arranged on a 400 foot (122 meters) test track with differing road conditions: wet roads, slippery roads, and rough roads. Two vehicles, a lead vehicle equipped with data sensors and a demonstration vehicle with internal display, continually circled the track to generate data. The lead vehicle collected the data and transferred the data to the server in one-minute intervals. The transferred data was then geocoded on the server side to link the road condition encountered by the lead vehicle with the appropriate section of the test track. This enabled a display set up within the demonstration vehicle to receive a notification of the upcoming road condition or weather event (MDOT 2016).

Over the combined 31 months of data collection from IMO 1.0 and 2.0, MDOT (2016) reported the following improvements and lessons learned that are specific to software, hardware, and web portal:

1. Software enhancements included an automated remote update that allows software upgrades to be pushed via the server to ensure that all vehicles in the study run the same version of software. The length of time before transferring a data file was reduced from every five minutes to every one minute. This allowed for a much-improved flow of data from vehicles and allowed the phones to keep up with the continual data collected while a vehicle was in operation.

2. Hardware lessons learned included the following items. First, special care or temporary removal of mobile RWIS should be in place when cleaning trucks, as these sensors were damaged when maintenance personnel utilized high-pressure washers to clean the winter maintenance trucks. Second, additional phones should be purchased as backups and continually upgraded when not in use to allow for minimal downtime when an original phone malfunctioned.

3. Web portal was redesigned to allow viewers to see vehicles in operation on a map of southern Michigan. It also allowed pictures that were taken by the vehicle to be seen on the portal so web users can see what the driver sees (MDOT 2016).

The third phase (IMO 3.0) started in 2018, and it focused on collecting weather-related observations from connected vehicles and mobile data-acquisition platforms such as a vehicle-based information and data acquisition system (VIDAS) (MDOT 2018a). MDOT's VIDAS system was used to replace the DataProbe system in the IMO 2.0 project due to its additional flexibility (MDOT 2018b). The VIDAS system converts the collected road condition and weather data into binary files to decrease the file sizes and minimize transmission costs of mobile RWIS data. On the server side, a newly developed data use analysis and processing (DUAP) system receives, ingests, quality checks, and analyzes the data for decision makers. In addition to the mobile RWIS data, the DUAP system also receives road condition and weather data from a variety of sources including the National Weather Service, MDOT fixed RWIS sites, the automated surface observation system, and the automated weather observing system (MDOT 2018a). The IMO 3.0 project, VIDAS system, and DUAP system were reported to show the viability for connected vehicle data to be used in identifying weather-related threats and hazards. Combining this information with other fixed and mobile data can provide additional coverage and details during weather events (MDOT 2018a).

IMO 3.0 also investigated the use and viability of data collected with other agencies' systems such as MDOT's weather response traffic information system (Wx-TINFO). The Wx-TINFO system leverages data from DUAP, VIDAS, and IMO to notify the traveling public with warnings, alerts, and advisory messages. This messaging allows the public to make more informed decisions before and while traveling Michigan's roadways during inclement weather using Michigan traveler information systems such as roadside dynamic message signs and the Mi Drive website, as shown in Figure 4 (MDOT 2014). In addition to advising the travelling public, MDOT is currently combining the IMO/mobile RWIS capabilities with the FHWA MDSS software to collect near real-time information about current roadway atmospheric conditions to provide decision makers with a more effective and efficient winter treatment system capable of realizing winter maintenance operational savings (MDOT 2013).

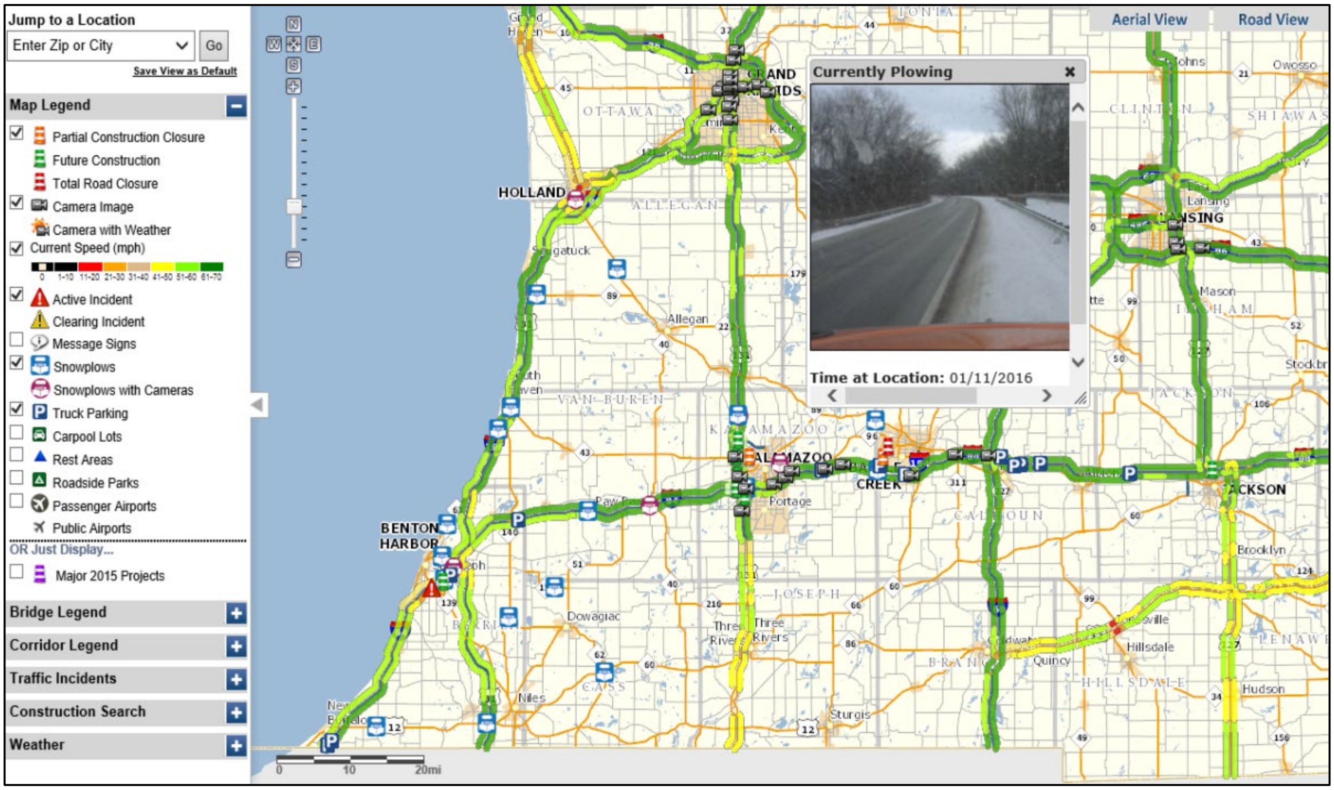


Figure 4. Screenshot. Mi Drive website interface with snowplow camera tracking (AASHTO 2017).

Minnesota Department of Transportation

In 2013, the Minnesota Department of Transportation (MnDOT) started deploying mobile RWIS on 329 MnDOT vehicles, including supervisor vehicles and winter maintenance trucks. MnDOT reported they have expanded their fleet of mobile RWIS-equipped vehicles to 590 vehicles as of 2017 (MnDOT 2013; AASHTO 2017). MnDOT has tested several mobile RWIS, including Lufft MARWIS, High Sierra Ice Sight, Teconer RCM411, and Vaisala DSP310 (MnDOT 2019). MDOT utilizes Pathways 1 and 2 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes cellular network and dedicated short-range communications, as shown in Table 1 (AASHTO 2017).

MnDOT was also part of the IMO research initiative sponsored by the FHWA Road Weather Management Program, as discussed in the “Cost Performance” section. MnDOT instrumented and deployed 478 heavy-duty trucks, 20 light-duty trucks, and 5 mowers with IMO sensors. The collected mobile road condition and weather observation data from IMO-equipped vehicles are combined with data from over 100 fixed RWIS sites, airport weather stations, weather radar, and weather forecasts at a centralized MnDOT server. This data is transmitted through a hybrid communication method using cellular communications, automated vehicle location, and dedicated short-range communications (FHWA 2019). The collected IMO data is transferred to and analyzed by the MnDOT MDSS to provide automated road advisories, warnings, treatment information, and recommendations for road maintenance (FHWA 2019). The MnDOT MDSS can generate unique forecasts and winter treatment recommendations for all 810 MnDOT plow routes (NOCE 2019).

MnDOT utilizes the combined capabilities of mobile RWIS and MDSS to provide winter maintenance treatment recommendations for each snowplow route. MnDOT personnel can make more informed decisions for maintenance planning and treatment actions through detailed, hour-by-hour weather and pavement forecasts provided by the MDSS. These informed decisions result in improved mobility and safety, as well as cost savings and reduced environmental impacts from reduced material usage (FHWA 2020b).

The combined capabilities of IMO and MDSS enable MnDOT to generate effective road advisories and warnings to provide the public with better information to make informed travel decisions, thereby improving safety and mobility. To augment the weather condition information in the agency's traveler information system, MnDOT provides road condition images taken from active plow vehicles in the field. This provides additional information on current and anticipated roadway dangers and conditions. MnDOT's dash cameras automatically record images of the road ahead of the plow whenever the mobile data collection (MDC) and automated vehicle location (AVL) system is on. Images are taken once every five minutes and only retained if the plow is moving at least 10 miles per hour. This is configurable and can be programmed to take images more frequently. The cameras can also take operator-initiated snapshots and video clips. Plow camera images are incorporated into several aspects of MnDOT's travel information system, including the desktop website, mobile website, and 511 App, as shown in Figure 5 (FHWA 2019).

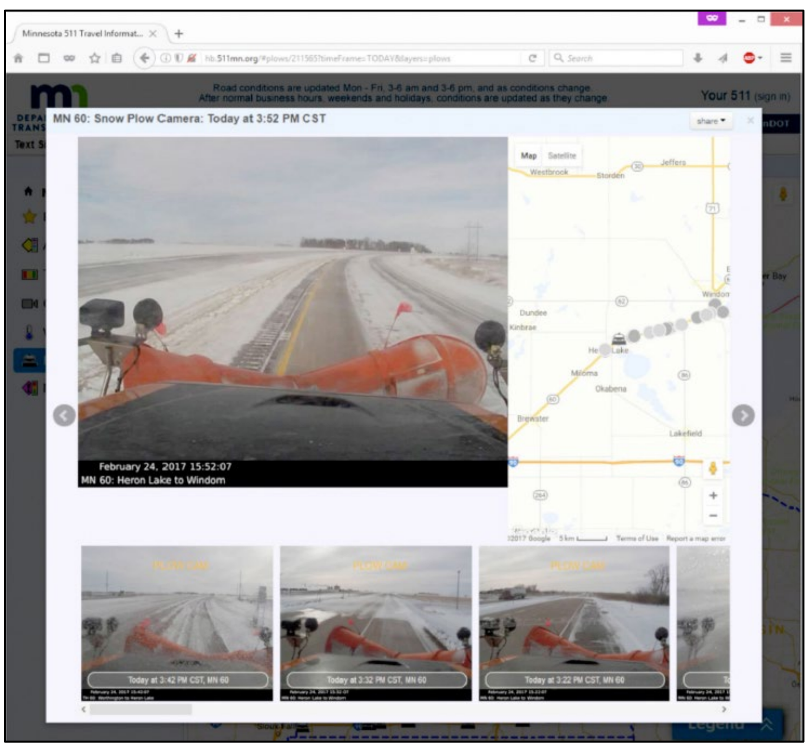


Figure 5. Screenshot. Plow camera image and map on MnDOT's 511 website (FHWA 2019).

The MnDOT MDSS leverages IMO data to provide more accurate and precise recommendations for maintenance decisions, including the appropriate amounts of salt and materials to apply. The provision of road condition images from plow vehicles on MnDOT's 511 traveler information system increases the situational awareness of the traveling public and MnDOT operators to make more informed decisions. The availability of mobile observations also allows the agency to better manage its vehicle fleet and assets during weather events. Overall, these efforts result in safer roadways, increased mobility, reduced environmental impacts from salt use, and a reduction in agency costs due to less material usage and increased efficiencies with staff time (FHWA 2019).

Indiana Department of Transportation

In 2006, the Indiana Department of Transportation (INDOT) started deploying mobile RWIS on 10 INDOT winter maintenance vehicles. INDOT reported they have expanded their fleet of mobile RWIS-equipped vehicles to 130 winter maintenance vehicles as of 2009 (INDOT 2007, 2009). The mobile RWIS models used in INDOT vehicles were not reported (INDOT 2009). INDOT utilizes Pathway 2 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes dedicated short-range communications, as shown in Table 1 (INDOT 2009).

In 2006, INDOT developed and tested an AVL system and MDC on 10 winter maintenance vehicles to collect measurements of road and weather conditions, road surface temperature, plow position, and chemical distribution. The collected data was transferred from the maintenance vehicle to INDOT utilizing the statewide wireless data network SAFE-T. This network is used by the Indiana State Police and other public agencies for coordination and response to routine, emergency, and catastrophic events. The collected road and weather data is sent through the SAFE-T radio network system to a central office in Indianapolis and then routed to a INDOT district or subdistrict office (INDOT 2007). The SAFE-T network provided real-time reporting and did not require additional hardware and cellular service costs (INDOT 2007). The road and weather data collected by each vehicle is mapped to illustrate time of chemicals placed, type of chemical, application rate, vehicle speed, road temperature, and plow position. This data can be integrated into MDSS to provide better information for winter maintenance decisions (INDOT 2007).

In 2008, INDOT decided to increase the MDSS from limited use (10 trucks) on a few routes to a representative sample (10%) of routes across six INDOT districts. INDOT purchased and installed 120 AVL/MDC units for their winter maintenance vehicles. Upon implementation, managers tracked salt use, labor overtime, and fuel usage over the 2008–2009 winter season. Equipping 10% of the INDOT fleet (120 vehicles) with AVL/MDC equipment cost approximately $895,207 and provided INDOT with realized savings of $10,957,672 in 2009. This includes material savings (salt/brine) of $9,978,536 and an overtime labor savings of $979,136. Approximately 228,470 tons of salt/brine were saved due to the combined use of AVL/MDC and MDSS, which represents a 40.9% lower salt usage compared to 2008. Fuel usage was also 13.7% lower in 2009 than in 2008. INDOT reported in 2009 that the use of AVL/MDC equipment on the INDOT fleet combined with MDSS implementation was a resounding success and was planning to investigate expanding the number of trucks equipped with AVL/MDC (INDOT 2009).

Note that the $13,468,501 actual cost savings in 2009 were then normalized by INDOT to account for varying snowfall and weather conditions in different winter seasons. The annual normalized cost savings that was estimated by INDOT for an average winter season was $10,957,672, which consists of material savings (salt/brine) of $9,978,536 and labor savings of $979,136 (INDOT 2009).

Ohio Department of Transportation

In 2017, the Ohio Department of Transportation (ODOT) started a pilot test by deploying mobile RWIS on ODOT supervisor vehicles. The mobile RWIS models used in MDOT vehicles include Lufft MARWIS (ODOT 2017, 2020). ODOT utilizes Pathway 1 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes cellular network, as shown in Table 1 (ODOT 2017, 2020).

In 2017, ODOT started testing mobile RWIS on supervisor vehicles to improve safety for motorists travelling on the I-90 snowbelt. The mobile RWIS were used to collect pavement condition data, including temperature, friction, and moisture (ODOT 2017). This roadway section was selected due to the frequency and severity of winter-related motor vehicle crashes. Over a 10-year span, more than 800 winter crashes were recorded along this corridor, including a 50-car pileup in 2016 (Roads and Bridges 2018). To reduce winter-related crashes on I-90, ODOT deployed mobile RWIS and constructed more fixed RWIS sites in order to introduce variable speed limits based on real-time road pavement condition, visibility, precipitation, vehicle incidents, and traffic congestion. For example, the maximum speed limit for the corridor is 70 mph, a moderate amount of precipitation may merit a 60 mph speed limit change, while drifting conditions or low visibility could further reduce the speed limit to 50 mph (Roads and Bridges 2018). Road condition and weather changes are communicated to motorists through dynamic message signs. ODOT Transportation Systems Management and Operations conducted a case study to evaluate the reduction in crashes realized by implementing variable speed limits. The agency reported that total crashes decreased by 22% and crashes while snowing decreased 42% despite a 15% increase in snow events (ODOT 2019; USDOT 2021).

ODOT (2020) recently reported that they utilized a number of their vehicles equipped with mobile RWIS in a research project to investigate the effects of tree canopy on pavement condition, safety, and maintenance. Tree canopies over rural highways caused concern for ODOT maintenance personnel, noting that excessive shading on the roadway during winter allowed snow and ice to remain on the pavement longer, which has the potential to increase potholes, create inconsistent road conditions for drivers, and cause cars to hydroplane due to moisture dripping onto ice-covered surfaces. Additionally, canopy coverage or shaded roadway sections have been reported to require increased maintenance by ODOT personnel (ODOT 2017). Mobile RWIS were used to measure the pavement temperature and moisture data as part of ODOT’s research project. The project concluded that tree canopies do not negatively affect pavement condition, safety, and maintenance except in unique conditions (ODOT 2020).

Colorado Department of Transportation

In 2006, the Colorado Department of Transportation (CDOT) started deploying mobile RWIS on 20 CDOT snowplows. CDOT reported they have expanded their fleet of mobile RWIS-equipped vehicles to 309 snowplows as of 2015 (CDOT 2011, 2015). The mobile RWIS models used in CDOT vehicles include Lufft MARWIS and Teconer RCM411 (CDOT 2011, 2015). CDOT utilizes Pathway 1 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes cellular network, as shown in Table 1 (CDOT 2011, 2015).

Since 2006, CDOT has used both mobile and fixed RWIS to collect real-time road condition and weather data to treat each specific road condition safely and effectively. Originally implemented in the Denver metropolitan area with 20 mobile RWIS snowplows, CDOT realized an annual savings of $1.2 million utilizing MDSS, reducing winter maintenance costs by nearly 19% than the previous year. In 2010, CDOT (2011) reported an increase in its number of mobile RWIS- and MDSS-equipped snowplows to 42 in the Denver area alone.

CDOT vehicles equipped with both mobile RWIS and MDSS provide the capability of generating unique road treatment recommendations for each route using a combination of reliable road condition prediction, accurate weather prediction, and effective rules of practice for anti-icing and deicing. This combined system of mobile RWIS and MDSS allows crews to input real-time conditions, including road and ambient temperature, type of snow-removal products being used, and the application rate, as shown in Figure 6. After comparing the information to 15 weather reports, the system provides suggested treatments based on the information and models. The system provides the vehicle operator with suggested treatments such as retreating the road later, applying different products at different rates, or continuing current treatments. This suggested treatment can then be implemented or overruled by the operator depending on their assessment of field conditions (CDOT 2011).

Figure 6. Photo. CDOT snowplows equipped with mobile RWIS and MDSS display (CDOT 2013).

Nevada Department of Transportation

In 2009, the Nevada Department of Transportation (NDOT) started deploying mobile RWIS on 20 NDOT vehicles, including 10 light-duty cars (supervisor vehicles) and 10 snowplows. NDOT reported they have expanded their fleet of mobile RWIS equipped vehicles to 60 vehicles as of 2017 (NDOT

2019). The mobile RWIS models used in NDOT vehicles include RoadWatch (NDOT 2019). NDOT utilizes Pathways 1 and 2 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes cellular network and dedicated short-range communications, as shown in Table 1 (AASHTO 2017).

In 2009, NDOT started a Winter Maintenance Improvements program that investigated the potential of utilizing mobile RWIS and MDSS. NDOT equipped 10 snowplows and 10 light-duty trucks with mobile RWIS and MDSS to collect real-time road and weather data. As of 2019, NDOT reported that it has 60 vehicles capable of acquiring weather data, including 9 snowplows with mobile RWIS (NDOT 2019). NDOT was also part of the IMO research initiative sponsored by the FHWA Road Weather Management Program discussed in the “Utilization of Mobile RWIS by State DOTs” section.

Nevada has unique “microclimates” in remote mountainous and local areas that present challenges in transmitting collected RWIS data. To address this challenge, this program focused on conducting preliminary evaluations of different forms of transmitting mobile RWIS data from remote locations to the NDOT central sever. While many state DOTs utilize cellular phone networks to transfer mobile RWIS data, this form of communication is not viable in Nevada, which has little to no cellular network coverage in remote locations. NDOT solved the communication problem by utilizing the existing NDOT Enhanced Digital Access Communications System (EDACS) radio system, which has data transmission capabilities (NDOT 2014). Initially, EDACS worked effectively for transmitting data from the winter maintenance vehicles to central NDOT. However, as more sensors were added to NDOT vehicles to measure additional road, weather, and vehicle data, the system was limited due to EDACS’s slow transfer time. To overcome this transmission limitation, NDOT developed a multimodal dedicated short-range communication and cellular network in 2014 to receive road, weather, and vehicle data from mobile vehicles throughout Nevada (NDOT 2016).

Based on the communication upgrades, NDOT conducted a pilot study to analyze the costs and benefits of implementing mobile RWIS and MDSS for winter maintenance operations. NDOT reported they can expect to see substantial savings if they choose to implement mobile RWIS and MDSS. Based on results from other state DOTs, NDOT reported they could save between $520 thousand to $1 million annually based on their salt/sand budget of $2.6 million (NDOT 2014).

California Department of Transportation

In 2005, the California Department of Transportation (Caltrans) started deploying mobile RWIS on four Caltrans vehicles, including two trucks and two snowplows. The mobile RWIS models used in Caltrans vehicles include RoadWatch (Caltrans 2015, 2019). Caltrans utilizes Pathway 1 in the federal guidelines for data communication between vehicles equipped with mobile RWIS and state DOT systems. This includes cellular network, as shown in Table 1 (Caltrans 2006, 2015, 2019).

The use of mobile RWIS was started by CalTrans in 2005 when it initiated a multiphase research project for snow-removal operations with the overall goal to design, build, and field test a mobile real-time information system for winter operations personnel, also known as “snow-fighter supervisors” (Caltrans 2006). This mobile real-time information system (MRTIS) is designed to improve the responsiveness of snow-removal equipment and crews, lower winter operational costs, and keep roads accessible (Caltrans 2006). This system collects road condition and weather information from a variety of sources, including mobile RWIS vehicles, fixed RWIS sites, weather forecasts, and Caltrans personnel observations (Caltrans 2006). This collected data is then utilized by MDSS to process and create more accurate local weather predictions and new applicable information for winter maintenance (Caltrans 2006). The MDSS was designed to provide snow-fighter supervisors with winter maintenance decision-making techniques capable of improving resource allocation decisions, enhancing efficiency, increasing safety, and minimizing environmental impact (Caltrans 2006).

The MRTIS research project was planned to be conducted in three sequential phases. The start and finish dates of each phase along with its stated objectives are summarized as follows:

- Phase 1 (June 2005–December 2006): Implement and demonstrate the capabilities of deploying mobile RWIS to measure road and weather data and communicate information to Caltrans.
- Phase 2 (June 2010–June 2011): Investigate available commercial systems and the existing Caltrans system to integrate mobile RWIS within Caltrans and across other state agencies.
- Phase 3 (June 2012–September 2015): Finalize system requirements, design, and development in a test fleet of four vehicles (two snowplows and two maintenance trucks).

The first phase of the research developed proprietary first-generation hardware and software for mobile RWIS, which was fully implemented and demonstrated in a research vehicle. This prototype on-board mobile RWIS system was designed to track the research vehicle's location, measure air and road temperature, communicate this information to a central location, and receive weather and other information from a central location (Caltrans 2015). The system implementation of this first-generation prototype was challenging; however, Caltrans was encouraged by its design and features and pursued the second phase of the research project. The second phase focused on expanding the first-generation prototype system developed in the first phase to include additional sensors, developing initial requirements for the deployment of the expanded prototype mobile RWIS, exploring commercially available mobile RWIS systems, and evaluating the communication capabilities of the existing Caltrans system. The original intent of the third phase was to finalize the system requirements, design, and develop the next-generation proprietary mobile RWIS system. Four prototypes (two full capable, two sensing and communicating only) were planned to be developed and installed on two supervisor vehicles and two snowplows to facilitate field testing and analysis. However, during the third phase, Caltrans officials decided in February 2014 to cancel the development of the next-generation proprietary Caltrans mobile RWIS system and instead consider utilizing commercially available systems developed by the RWIS manufacturer Vaisala. The Vaisala system lacked vehicle-specific sensor information such as plow and wing deployment, rock, sand, or chemical dispersal, vehicle-to-vehicle messaging, and vehicle safety features; however, it was commercially available and could be readily deployed by Caltrans (Caltrans 2015, 2019). As of 2019, Caltrans started another pilot study to investigate the use and integration of commercially available hardware mobile RWIS systems with Verizon systems that are currently installed on Caltrans heavy fleet vehicles.

Survey of Mobile RWIS Use by State DOTs

This section summarizes the findings of the literature review on a 2017 survey conducted by the Montana Department of Transportation (MDT) on the state of practice of RWIS. The survey was sent to all 50 states, Washington DC, Puerto Rico, and the Canadian provinces. MDT received 28 survey responses from 24 different state DOTs and two Canadian provinces. The survey focused on the state of practice of fixed and mobile RWIS use, management, data, and planning. Relevant questions in this survey focused on the following RWIS topics: (1) use of RWIS data; (2) current use of mobile RWIS; (3) current funding of mobile RWIS; (4) future funding of mobile RWIS; (5) parameters measured by RWIS; (6) plans to expand fixed and mobile RWIS; (7) software used for RWIS data; and (8) additional comments. Key findings of the eight survey questions are summarized below:

1. Use of RWIS data: Transportation officials were asked to identify the primary and secondary use of RWIS data. Twenty-four survey respondents reported that the primary use of RWIS data was winter maintenance support, and its secondary use was providing travel information to drivers including weather warnings and automated dynamic message signs.

2. Current use of mobile RWIS: Respondents were asked if they currently utilize mobile RWIS. Three survey respondents reported they use mobile RWIS as an essential part of the winter maintenance program, 9 respondents reported they use mobile RWIS as part of an experimental program, and 14 respondents reported they do not use any mobile RWIS.

3. Current funding of mobile RWIS: Survey respondents were asked to identify the percent of current funding/efforts spent toward mobile RWIS vs traditional fixed RWIS. Fifteen transportation agencies reported they devote no funding or efforts to mobile RWIS, nine agencies reported they use low funding (10% or less) toward mobile RWIS, and one agency reported they use moderate funding (10%–50%).

4. Future funding of mobile RWIS: Agency personnel were asked to speculate on the percentage of future funding/efforts that will likely go toward mobile RWIS vs fixed RWIS five years from now. Four agencies reported devoting no funds/effort toward mobile RWIS, seven agencies reported low funding (1%–10%) of future funding/efforts would go toward mobile RWIS, eight agencies reported moderate funding (11%–50%) toward future mobile RWIS, and one agency reported high funding (51%–100%) toward future mobile RWIS.

5. Parameters measured by RWIS: Transportation officials were asked to identify the "must-have" parameters measured by RWIS. The "must-have" parameters, ranked highest to lowest, include pavement temperature, air temperature, pavement condition, wind speed and direction, precipitation occurrence, precipitation intensity/depth, humidity, and visibility.

6. Plans to expand fixed and mobile RWIS: Survey respondents were asked to identify their plans for RWIS program expansion. Eighteen agencies are continuing to expand their fixed RWIS sites, eleven agencies are satisfied with their current RWIS configuration, and five agencies are planning on adding mobile RWIS.

7. Software used for RWIS data: Agency personnel were asked to identify the software used for RWIS data. Fifteen agencies reported they use Vaisala software, ten agencies reported they use their own custom software, one agency reported they use Delcan software, and one agency reported they use Lufft software.

8. Additional comments: The additional comments from transportation officials varied; however, the expansion of mobile RWIS and integration with their ITS programs was repeated among several survey respondents.

PERFORMANCE OF MOBILE ROAD WEATHER INFORMATION SENSORS

This section summarizes the reported performance of mobile RWIS by state DOTs. The reported performance of mobile RWIS in this chapter are organized into three categories: (1) cost performance, (2) additional benefits, and (3) reported challenges and current solutions.

Cost Performance

Several state DOTs have analyzed the costs and benefits of integrating mobile RWIS and MDSS into winter road maintenance operations, as shown in Table 2. INDOT kept track of their AVL and MDC equipment as well as MDSS implementation costs, overtime labor savings, and material (salt/brine) savings during the winter season of 2008–2009 (INDOT 2009). As stated earlier in the "Indiana DOT" section, INDOT reported a total cost of $895,207 for the installation of AVL/MDC equipment on 120 INDOT vehicles in 2008. The use of these mobile RWIS-equipped vehicles provided INDOT with realized savings of $10,957,672 in 2009. This includes material savings (salt/brine) of $9,978,536 and an overtime labor savings of $979,136.

In 2009, South Dakota Department of Transportation (SDDOT) analyzed the benefits and costs of MDSS in three states: New Hampshire, Minnesota, and Colorado. These three states were selected from FHWA pooled-fund study participants to represent varying winter weather conditions in the US (SDDOT 2009). The annual implementation cost of statewide deployment of mobile RWIS equipment and MDSS in New Hampshire, Minnesota, and Colorado were estimated to be $332,879, $496,952, and $1,497,985, respectively (SDDOT 2009). These annual costs were estimated by calculating the required costs for hardware, software, tech support, communications, training, administrative, and weather forecast provider costs. The annual savings that can be realized by deploying these mobile RWIS and MDSS in New Hampshire, Minnesota, and Colorado were estimated to be $2,367,409, $3,179,828, and $3,367,810, respectively (SDDOT 2009). These annual savings were estimated based on the MDSS utilizing existing DOT resources to provide the same level of service (SDDOT 2009).

As shown in Table 2, the return on investment for deploying mobile RWIS equipment and MDSS in Indiana, New Hampshire, Minnesota, and Colorado is estimated to be 1,124%, 611%, 540%, and 125%, respectively. These impressive return-on-investment numbers highlight the significant DOT savings that can be realized by deploying mobile RWIS equipment and MDSS.

Table 2. Cost-Benefit Analyses Reported by Other State DOTs (INDOT 2009; SDDOT 2009)

State DOT	Implementation Cost	Annual Labor Savings	Annual Material Savings	Annual Total Savings	Return on Investment	Payback Period (in Years)
Indiana	$895,207*	$979,136	$9,978,536	$10,957,672	1,124%	0.08
New Hampshire	$332,879 / year	Not Specified	Not Specified	$2,367,409	611%	0.14
Minnesota	$496,952 / year	Not Specified	Not Specified	$3,179,828	540%	0.16
Colorado	$1,497,985 / year	Not Specified	Not Specified	$3,367,810	125%	0.44

*Does not include training or communication costs

Additional Benefits

In addition to the cost benefits, there were a number of additional qualitative benefits reported by state DOTs that utilized mobile RWIS and/or MDSS to improve winter maintenance operations. These benefits are grouped in this report in three categories: (1) agency benefits, (2) motorist benefits, and (3) environmental and societal benefits.

Agency Benefits

The main benefit reported by DOTs that utilized mobile RWIS and MDSS was the significant reduction in the use of winter maintenance resources. This reduction in snow- and ice-control materials and chemicals were reported to provide many additional benefits to DOTs such as reduced corrosion to vehicles and trucks; reduced deterioration of transportation infrastructure and other assets; demonstration of environmental stewardship and policy compliance; and better road customer satisfaction. Some of these benefits can be potentially considered tangible yet are difficult to quantify in monetary terms (SDDOT 2009).

Another transportation agency benefit is reducing the maintenance cost of roadway winter maintenance vehicles and expanding their service life. SDDOT estimated that improved efficiency and effectiveness of winter maintenance operations would enable MnDOT to experience nearly 30% fewer maintenance vehicle issues per year (SDDOT 2009; MDT 2017).

Motorist Benefits

The integration of mobile RWIS and MDSS in winter maintenance operations provide significant benefits for motorists in the form of safer roads, fewer delays and winter-related accidents, reduced operating and fuel costs, and improved level of service during winter events (SDDOT 2009). Adoption of mobile RWIS and MDSS can further improve DOT response and treatment of roads affected by winter weather events, thereby reducing safety risk during inclement weather. Weather-related crashes account for 1,235,145 crashes each year, which represents approximately 21% of all vehicle crashes (FHWA 2021).

Environmental and Societal Benefits

Many environmental benefits of deploying mobile RWIS and MDSS can be realized through more efficient and reduced use of snow- and ice-control materials and chemicals during winter maintenance activities. This reduction in winter maintenance materials and chemicals can provide significant benefits to the adjacent environment (e.g., water, vegetation, and wildlife). This in turn can improve water quality, wildlife habitat, and air quality (SDDOT 2009). CDOT reported the use of sand/salt mixtures in winter maintenance operations can damage aquatic life as large amounts of silt are washed into streams (CDOT 2021).

Societal benefits of deploying mobile RWIS and MDSS can be realized through improved travel information including localized real-time road and weather conditions. Road weather information websites provide the public with more timely and valuable information, allowing them to make safer decisions both pre-trip and en-route during inclement weather conditions (MDOT 2014).

Challenges and Solutions

This section focuses on reported challenges of implementing mobile RWIS and solutions that have been adopted to address these challenges. These reported problems are grouped into two categories: (1) sensor setup and logistic challenges and (2) communication and data challenges.

Sensor Setup and Logistics Challenges

The most common reported challenge facing the use of mobile RWIS is that their optical sensors are susceptible to damage and/or require lens cleaning, as winter road slush and debris can cause problems if the sensing lens becomes obstructed (PB & Iteris 2013; MDT 2017). To reduce these optical sensor issues, mobile RWIS manufacturers have developed longer protective lens shields to reduce optical obstructions, as shown in Figure 7-a. Similarly, mounting mobile RWIS units on vehicle roofs can also significantly reduce road slush and debris from obscuring lenses, as shown in Figure 7-b (Lufft 2021).

(a) Longer Protective Shield (b) Mounting RWIS Units on Vehicle Roofs

Figure 7. Photo. Solutions for RWIS optical sensor obstruction challenges (Lufft 2021).

Another reported challenge of deploying mobile RWIS is identifying the best mounting location of RWIS units on snowplows. For example, DOTs have reported that the mounting of RWIS units in the discharge path of the snowplow can damage the sensor and/or provide poor results due to the amount of discharged snow (PB & Iteris, 2013). To overcome this challenge, manufacturers have recommended that mobile RWIS units mounted on snowplows should be placed away from the discharge area of the plow (see Figure 8-a) or further down the wheel house of the plow, as shown in Figure 8-b.

(a) Mounting RWIS unit away from snowplow discharge area

(b) Mounting RWIS unit along wheelhouse

Figure 8. Photo. Solutions for snowplow-mounted mobile RWIS.

A third challenge that is often encountered during the use of mobile RWIS is improper mounting and/or calibration. The accuracy of mobile RWIS measurements is affected by sensor distance and installation angle. Manufacturers factory calibrate their mobile RWIS units to DOT-specified heights and angles when RWIS units are ordered. Changing the location of the mobile RWIS unit can affect the accuracy or lead to unusable data (MnDOT 2019). To overcome this challenge, mobile RWIS manufacturers have introduced field calibration to adjust for different installation mounting geometries. If the mobile RWIS does not exceed the manufacturer-recommended mounting distance or angle, then the duration of field calibration can be less than a minute (MnDOT 2019).

Communication and Data Challenges

Cellular communications are a primary challenge for DOTs that operate in rural areas that have limited or no cellular service, or mountainous areas with topographies that block cellular networks. This significantly reduces the effectiveness and reliability of receiving accurate road and weather data (MDT 2017). To overcome this challenge, some state DOTs including Indiana, Nevada, Colorado, and Wyoming utilize either dedicated short-range communications or data storage within the mobile RWIS-equipped vehicle until communications can be resumed (INDOT 2007; NDOT 2019). The localized vehicle data storage does not provide “real-time” data solution; however, it still provides the capability of collecting the required data and transmitting it as soon as cellular network signals are restored (INDOT 2007).

COMMERCIAL MOBILE ROAD WEATHER INFORMATION SENSORS

This section presents the findings of the conducted literature review that focused on identifying commercially available mobile RWIS models used by state DOTs and their reported performance (AASHTO 2017; CDOT 2011, 2015; MDOT 2016; MnDOT 2013, 2019; NDOT 2019; ODOT 2017). Note that the literature review findings in this section are based on the latest reports published by state DOTs; therefore, these findings might not accurately represent the current use of RWIS models by state DOTs if they have expanded or changed their use of RWIS units in recent months or years after the publication of these reports. The analyzed commercially available mobile road and weather information sensor models in this section are summarized in Table 3.

Mobile RWIS Models Used by State DOTs

This section lists mobile RWIS models used by state DOTs to measure (a) road parameters, including road condition (dry, moist, wet, ice, snow, chemically wet), road surface temperature, water film height, ice percentage, and friction, and (b) weather parameters, including ambient air temperature, dew point temperature, and relative humidity.

Lufft MARWIS

The Lufft Mobile Advanced Road Weather Information Sensor (MARWIS) system (see Figure 9) is the most widely used mobile RWIS model by state DOTs. Several agencies are currently using or testing Lufft MARWIS, including Arkansas Highway Department; Minnesota, Missouri, Indiana, North Dakota, Nevada, Ohio, New York City, and Colorado DOTs; Michelin Tire Company (for tire testing); and several school districts on the east coast.

(a) Lufft MARWIS

(b) Version 1 wheelhouse height mounting (3 feet)

(c) Version 2 roof mounting (6 feet)

Figure 9. Photo. Lufft MARWIS and available mounting options (Lufft 2021).

Table 3. Mobile Sensors, Measured Parameters, and Hardware Cost

Parameters	Lufft MARWIS	Teconer RCM411	Vaisala MD30	Vaisala DSP310	High Sierra Elec. IceSight	PreCise ARC System	RoadWatch	High Sierra Elec. Surface Sentinel
Road Conditions (dry, moist, wet, ice, snow, slush, chemically wet)	✓ All six conditions	✓ Five conditions No chemically wet	✓ Five conditions No chemically wet	✓ Five conditions No chemically wet	✓ Five conditions No chemically wet			
Road Surface Temperature	✓	✓	✓	✓	✓	✓	✓	✓
Water Film Height	✓ Up to 6mm	✓ Up to 3mm	✓ Up to 5mm	✓ Up to 2mm				
Ice Percentage	✓							
Friction	✓ Calculated	✓	✓	✓	✓ Calculated			
Ambient Air Temperature	✓	✓	✓	✓	✓	✓	✓	✓
Dew Point Temperature	✓	✓	✓	✓				
Relative Humidity	✓	✓	✓	✓	✓	✓		
Current Use by DOTs	ARDOT, MNDOT, MODOT, INDOT, NDDOT, NDOT, ODOT, CDOT, and NYCDOT	MNDOT	MDOT, MNDOT and ODOT	Not Reported	MNDOT and NYSDOT	AKDOT, ADOT, CTDOT, IDOT, IADOT, MnDOT, MDDOT, NDOT, NYSThruway, NDDOT, ODOT, SDDOT, TDOT, WSDOT, and WYDOT	CALTRANS and NDOT	Not Reported
Hardware Cost	$10,700	$9,000	N/A	Unavailable	$ 6,680 Software $360/yr Cell Data $220/yr	$918	$600	$ 1,260 Software $360/yr Cell Data $220/yr

Lufft MARWIS was released in 2014 and measures road condition (dry, moist, wet, ice, snow, chemically wet), road surface temperature, ambient air temperature, water film height up to 0.25 in. (6 mm), dew point temperature, relative humidity, ice percentage, and friction, which is calculated based on the other measured parameters. These measurements are taken up to 100 times per second with a maximum output rate of 10 Hz and data output that supports the UMB (Universal Measurement Bus) binary protocol. MARWIS utilizes open interface protocols that can be easily integrated into existing winter maintenance monitoring networks. Similarly, the mobile road sensor can communicate directly with the control system on winter maintenance vehicles through Bluetooth, serial communication (RS485), or the vehicles' internal controlled area network (CAN Bus). The operating temperature is −40 to 140°F (−40 to 60°C) and operating relative humidity is from 0% to 100%. MARWIS is available in two versions for installation on vehicles at distances of 3 to 6 ft (1 to 2 m). Version 1 takes measurements at approximately 3 ft (1 m) and is often used on trucks with mounting at the height of the wheelhouse, while Version 2 takes measurements at approximately 6 ft (2 m) and is often used on cars with MARWIS mounting on the roof of the car, as shown in Figure 9 (Lufft 2021). The hardware cost of either version is approximately $10,700.

The anticipated useful life of each sensor is unknown due to the nature of a newer product, but Lufft reported they had several sensors in the field for over four years that are still operational. MARWIS sensors are available directly from Lufft or from any of their four channel partners, which cover over 30 states (MnDOT 2019).

Teconer RCM411

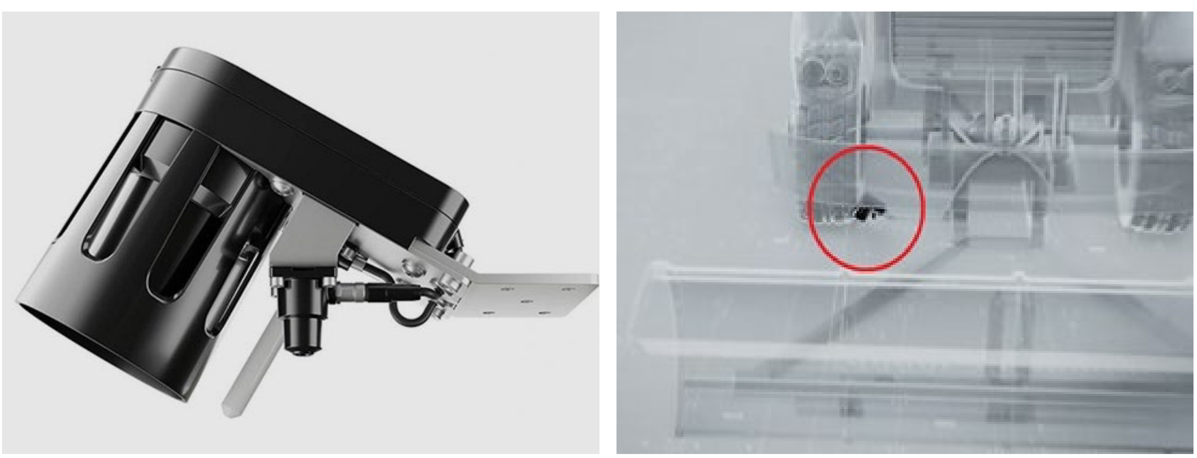
The Teconer Road Condition Monitor (RCM 411) was reported to be used by MnDOT as well as other international road and airport agencies (MnDOT 2019). Teconer RCM411 was developed in 2009 and measures road condition (dry, moist, wet, ice, snow, slush), road surface temperature, ambient air temperature, water film height up to 0.125 in. (3 mm), dew point temperature, relative humidity, and friction which is calculated based on the other measured parameters. The Teconer RCM411 communicates with a cell phone or the control system on winter maintenance vehicles through Bluetooth or serial port (RS-232). The operating temperature of the Teconer RCM411 is −22 to 122°F (−30 to 50°C). The manufacturer-recommended mounting distance from the pavement surface for the Teconer RCM411 is approximately 20 to 22 in. (51 to 56 cm). with a maximum mounting distance of 6 ft (2 m). Teconer provides a mounting design that is capable of using the 2 in. (50 mm) ball joint towing hitch, as shown in Figure 10 (MnDOT 2019; Teconer 2021). The hardware cost for the RCM411 is approximately $9,000. The reported useful life of the Teconer RCM411 sensor is approximately 10 years (MnDOT 2019).

(a) Teconer RCM411 (b) Tow hitch mounting

Figure 10. Photo. Teconer RCM411 and tow hitch mounting option (Teconer 2021).

Vaisala Mobile Detector MD30

Vaisala Mobile Detector MD30 is a compact mobile road and runway condition sensor that was specifically designed for snowplows and reported to be used by Michigan, Minnesota, and Ohio DOTs. The MD30 measures road condition (dry, moist, wet, ice, and snow), road surface temperature, ambient air temperature, water film height, dew point temperature, relative humidity, and friction, which is calculated based on the other measured parameters. The MD30 sends the measured data via Bluetooth to a smartphone to display the data. Data can be sent via smartphone to Vaisala road weather management software or other MDSS systems. The operating temperature is −40 to 140°F (−40 to 60°C) and operating relative humidity is from 0% to 100% (Vaisala 2021). The MD30 can be mounted from 7 to 43 in. (20 to 110 cm), as shown in Figure 11.



(a) Vaisala MD30 (b) Snowplow mounting on front bumper

Figure 11. Photo. Vaisala MD30 and snowplow mounting option (Vaisala 2021).

Vaisala Condition Patrol DSP310

Vaisala Condition Patrol DSP310 was released in 2012 and is currently unavailable for purchase, as it is under redevelopment by Vaisala (MnDOT 2019). The DSP310 measures road condition (dry, moist, wet, ice, and snow), road surface temperature, ambient air temperature, water film height, dew point temperature, relative humidity, and friction, which is calculated based on the other measured parameters. The DSP310 sends the measured data to a central processor that is attached to a smartphone device to display the data. The DSP310 reports data at a frequency of one measurement per three seconds. Data can be sent via smartphone to Vaisala road weather management software or other MDSS systems. The operating temperature is −40 to 140°F (−40 to 60°C) and operating relative humidity is from 0% to 100% (Vaisala 2021).

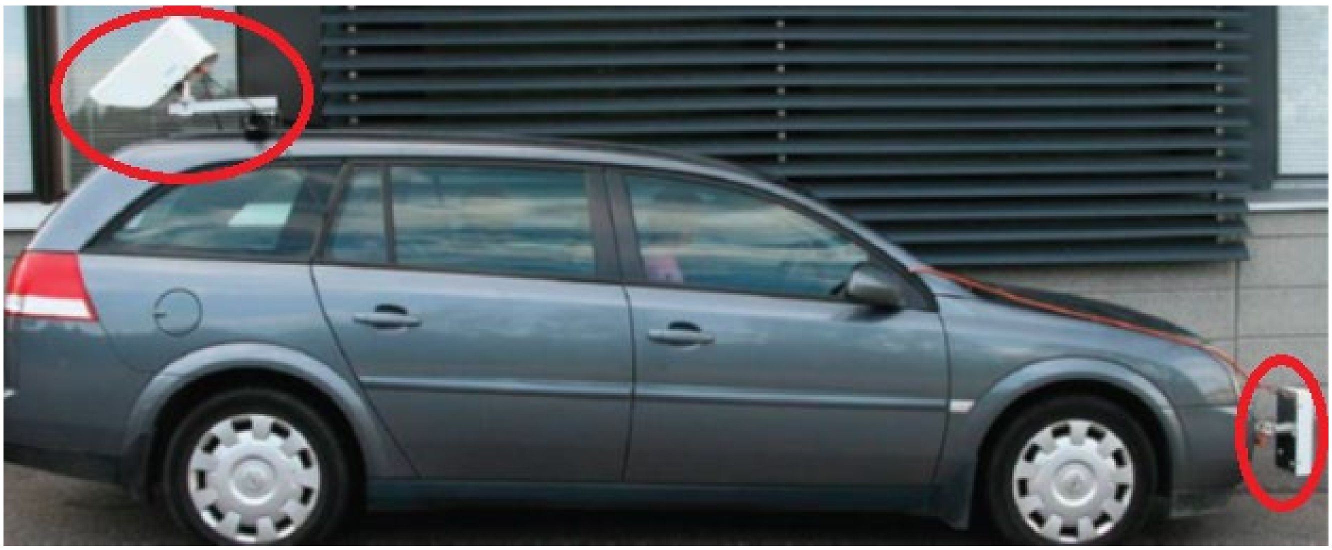
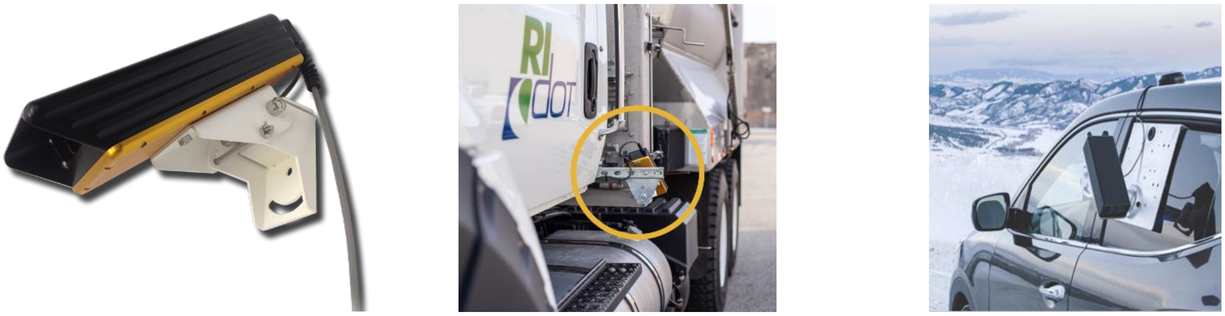


Figure 12. Photo. Vaisala DSP 310 and vehicle mounting (Vaisala 2021).

High Sierra Electronics Mobile IceSight

The Mobile IceSight system is manufactured by High Sierra Electronics. It was reported to be used by Minnesota DOT and the New York State DOT (MnDOT 2019). The Mobile IceSight Model 5435 pavement surface condition sensor was released in 2015. It is a remote mobile surface condition sensor that provides real-time surface condition and atmospheric information from a moving vehicle. The Mobile IceSight measures road condition (dry, moist, wet, ice, snow, slush), road surface temperature, ambient air temperature, relative humidity, and friction, which is calculated based on the other measured parameters. The Mobile IceSight does not measure water film height, dew point, and ice percentage. The Mobile IceSight transmits data to the control system on winter maintenance vehicles through serial port (RS-232), serial communication (RS485), or Wi-Fi communication. The operating temperature is −40 to 185°F (−40 to 85°C) and operating relative humidity is from 0 to 100%. Mobile IceSight can be mounted at ranges from 3 to 15 ft (1 to 4.5 m), as shown in Figure 13 (HSE 2021). The hardware cost is approximately $6,680, not including the $360 per year Contrail Connect Software subscription and $220 per year cellular data plan (25 MB per month) (HSE 2021). The reported useful life of the Mobile IceSight sensor is 5 to 10 years.



(a) HSE Mobile IceSight (b) Truck wheel height mounting (c) Vehicle window mounting

Figure 13. Photo. High Sierra Electronics Mobile IceSight and mounting options (HSE 2021).

PreCise MRM ARC System

The PreCise MRM Air and Road Condition (ARC) System was reported to be used by the New York State Thruway as well as the Washington State, Wyoming, Arizona, North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Wisconsin, Illinois, Tennessee, Ohio, Connecticut, Maryland, and Alaska DOTs. The ARC sensor measures road surface temperature, ambient air temperature, and humidity. The Air and Road Condition System does not measure road condition (dry, moist, wet, ice, snow, slush, chemically wet), water film height, dew point temperature, ice percentage, and friction. The Air and Road Condition System transmits data to LCD display through either a wired or wireless option; the mobile display connects to the winter maintenance vehicles through serial port (RS-232) or an M8 connector. The operating temperature is −40 to 185°F (−40 to 85°C) and can be mounted at ranges up to 33 ft (10 m), as shown in Figure 14 (FA 2021). The Air and Road Condition System has a hardware cost of $918.

(a) Wireless sensor option (b) Wired sensor option

Figure 14. Photo. PreCise Air and Road Condition System sensor (FA 2021).

RoadWatch

The RoadWatch sensor was reported to be used by NDOT and Caltrans (NDOT 2019; Caltrans 2019). The RoadWatch Sensor is a compact unit that measures road surface temperature, ambient air temperature, and GPS data. RoadWatch does not measure road condition (dry, moist, wet, ice, snow, slush, chemically wet), water film height, dew point temperature, relative humidity, ice percentage, and friction. The collected data is sent to the winter maintenance vehicle through serial port (RS-232), or Bluetooth adapter. The RoadWatch Sensor has a hardware cost of approximately $600 and is compact enough to be mounted on the mirror of winter maintenance vehicles, as shown in Figure 15 (RoadWatch 2021).

(a) RoadWatch sensor kit with display

(b) RoadWatch mirror mounting

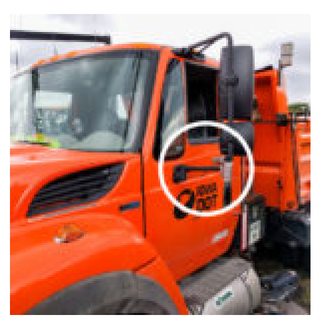
Figure 15. Photo. RoadWatch sensor and mirror mounting (RoadWatch 2021).

High Sierra Electronics Mobile Surface Sentinel

The High Sierra Electronics Mobile Surface Sentinel sensor measures road surface temperature and ambient air temperature. The Mobile Surface Sentinel does not measure road condition (dry, moist, wet, ice, snow, slush, chemically wet), water film height, dew point temperature, relative humidity, ice percentage, and friction. The Mobile Surface Sentinel transmits data to an LCD display via Bluetooth connection, the mobile display connects to the winter maintenance vehicles through serial port (RS-232), or serial communication (RS485). The operating temperature is −40 to 185°F (−40 to 85°C) and operating relative humidity is from 0 to 100%. Surface Sentinel can be mounted at ranges from 1.5 to 15 ft (0.5 to 4.5 m), as shown in Figure 16 (HSE 2021). The Mobile Surface Sentinel provides limited measurements compared to the Mobile IceSight but is significantly cheaper with a hardware cost of approximately $1,260, not including the $360 per year Contrail Connect Software subscription and $220 per year cellular data plan (25 MB per month) (HSE 2021).

(a) HSE Mobile Surface Sentinel and display unit

(b) Truck bumper mounting



(c) Truck mirror mounting

Figure 16. Photo. Mobile Surface Sentinel and mounting options (HSE 2021).

Accuracy of Analyzed Mobile RWIS Models

This section summarizes the reported accuracy of four mobile RWIS models that were analyzed in the "Mobile RWIS Models Used by State DOTs" section: Lufft MARWIS, Teconer RCM411, High Sierra IceSight, and Vaisala DSP310. These four mobile RWIS were tested as part of a Clear Roads pooled-fund research project to analyze the accuracy of the sensors in measuring four parameters: pavement temperature, air temperature, relative humidity, and water film height (MnDOT 2019). These tests were conducted on the Minnesota Department of Transportation's MnROAD test track. External sensors were used to take baseline measurements of the tested parameters. The mobile RWIS measurements of surface temperature, air temperature, relative humidity, and water film height were compared to the baseline measurements. A total of 29 measurements were taken for each mobile RWIS model in each tested parameter. Table 4 summarizes the average error of each mobile RWIS in each tested parameter. The Lufft MARWIS had the highest accuracy (lowest average error) in three of the four parameters (road surface temperature, ambient air temperature, and relative humidity), while the Vaisala DSP310 had the lowest average error in water film height (MnDOT 2019).

Table 4. Average Error of Mobile RWIS Models (MnDOT 2019)

Tested Parameters MNROAD Facility	Lufft MARWIS	High Sierra Elec. IceSight	Teconer RCM411	Vaisala DSP310
Road Surface Temperature (Average Error in °F)	**2.04°F**	3.75°F	2.94°F	2.07°F
Water Film Height (Average Error in mm)	0.171 mm	N/A	0.202 mm	**0.119 mm**
Ambient Air Temperature (Average Error in °F)	**1.39°F**	2.55°F	5.50°F	4.44°F
Relative Humidity (Average Error in %RH)	**6.48% RH**	7.58% RH	N/A	8.38% RH

Bold Indicates Best Performance Category

The four sensors evaluated by the MnDOT study were Lufft MARWIS, Teconer RCM411, High Sierra Mobile IceSight, and Vaisala DSP310. Throughout the study, sensors performed similarly, and no sensor was shown to be universally the best or worst across all parameters. The measurable differences among mobile RWIS were reported in that study to be very small. Accordingly, the study reported that agencies interested in procuring mobile RWIS should consider additional factors such as cost, installation/mounting, parameters measured, connections and communication, user interface, and maintenance (MnDOT 2019).

CHAPTER 3: STATE DOTS' BEST PRACTICES FOR MOBILE RWIS AND MDSS

This chapter presents the findings of the conducted interviews with other state DOTs to gather and analyze their experiences and best management practices for the deployment and use of mobile RWIS and MDSS. This analysis was performed in three steps that focused on (1) identifying state DOTs with experience in utilizing mobile RWIS and MDSS; (2) developing interview questions for DOT officials; and (3) conducting interviews with the identified DOT officials in the first step to gather and analyze their experiences for implementing and utilizing mobile RWIS and MDSS. The following sections provide concise discussion of the completed research work in each of these three steps.

IDENTIFIED STATE DOTS AND DOT PERSONNEL

To maximize the effectiveness of the conducted interviews, the research team worked with the Technical Review Panel (TRP) to identify a list of state DOTs with similar geography and climate to Illinois and with experience in utilizing mobile RWIS and MDSS. A list of contacts was obtained from the TRP for each identified state DOT. The list of contacts for state DOT officials consisted of members of the "Clear Roads" research program that includes US transportation professionals and researchers who focus on promoting innovation for roadway winter maintenance operations (CR 2021). Table 5 summarizes the interviewed state DOT personnel, their bureau/division, job title, and date and time of the interview. All interviewed state DOT personnel indicated they are responsible for all aspects of mobile RWIS and MDSS.

Table 5. Interviewed State DOT Personnel

State DOT	Name	Job Title	Bureau/Division	Date and Time of Interview
Colorado	Jamie Yount	Winter Operations Program Manager	Maintenance and Operation	October 11, 2021 2:00 p.m. CT
Indiana	Jeremy McGuffey	Statewide Winter Operations Manager	Highway Maintenance	October 14, 2021 11:00 a.m. CT
Michigan	Justin Droste	Region Support Engineer	Maintenance Services	October 25, 2021 2:00 p.m. CT
Minnesota	Jeffrey Jansen	Road Weather Technology Team Leader	Office of Maintenance	October 6, 2021 1:00 p.m. CT

Developed Interview Questions

The interview questions were developed following the best practices guidelines of the American Association for Public Opinion Research (AAPOR 2021). The interview questions were designed to be open ended to allow for further discussion and elaboration during the conducted interviews. The interview questions were designed in collaboration with the TRP of this project to collect feedback and data from interviewed DOT officials on their prior experiences with mobile RWIS and MDSS. The developed interview consisted of 28 questions organized and grouped in eight sections, as shown in Table 6 and Table 7. Each identified DOT official was first contacted by the TRP Chair to seek their availability for an online interview, and then contacted by the research team to schedule the interview. Members of the TRP were invited to each interview to facilitate an open discussion with the interviewed DOT officials. The interviews were conducted through video conferencing software (Zoom Meetings) and recorded by the research team. The research team shared their screen containing the interview questions so all attendees could follow along and ask follow-up questions as necessary.

CONDUCTED INTERVIEWS

The research team scheduled video conference meetings to interview each of the DOT officials listed in Table 5. These interviews were conducted from October 6, 2021, to October 25, 2021, with representatives of the TRP. The interview consisted of 28 questions organized and grouped in eight sections, as shown in Table 6 and Table 7. The interview questions were designed to collect feedback from DOT officials on their (1) background information of mobile RWIS and MDSS use; (2) use of mobile RWIS hardware and related implementation; (3) use of mobile RWIS and MDSS software and communications; (4) mobile RWIS and MDSS costs and savings; (5) encountered challenges utilizing mobile RWIS and MDSS; (6) required maintenance for mobile RWIS; (7) mobile RWIS data use, storage, and retention; and (8) additional feedback on mobile RWIS and MDSS. The complete interview questionnaire is shown in the appendix. The DOT officials were forwarded the interview questions (see Table 7) in advance to provide them with adequate preparation time. The following sections provide a concise description of the interview procedure and its findings on the use of mobile RWIS and MDSS by other state DOTs.

Table 6. Organization of State DOT Interview Questions

Section	Number of Questions
1. Background Information	2
2. Mobile RWIS Hardware and Implementation	8
3. Mobile RWIS Software and Communications	4
4. Mobile RWIS and MDSS Costs and Savings	3
5. Challenges of Mobile RWIS and MDSS	3
6. Mobile RWIS Maintenance	3
7. Mobile RWIS Data Use, Storage, and Retention	3
8. Discussion	2

Table 7. Interview Questions for State DOT Officials

Interview Questions
1.1. What is your name, title, and bureau/group?
1.2. How long have you been using mobile RWIS and/or MDSS?
2.1. Use of mobile RWIS: a. What types/models are currently used in your state? b. What types/models have you used in the past but are not currently used? c. What are the factors/reasons for your current selection? d. Did you have any DOT procurement constraints/issues?
2.2. List the total number in your fleet and the number of vehicles equipped with mobile RWIS.
2.3. Describe the mounting location of mobile RWIS on the vehicles.
2.4. What criteria did you use to select travel routes for vehicles with mobile RWIS?
2.5. What is your current coverage with mobile RWIS/MDSS and what is your planned expansion in the next 3-5 years?
2.6. What training was provided for mobile RWIS/MDSS use and who provided the training?
2.7. How is pre-plowed, and post-plowed data utilized?
2.8. Is the collected mobile RWIS data integrated automatically into public road condition reports?
3.1. Does your state utilize MDSS in conjunction with mobile RWIS? a. If yes, what MDSS software does your state use? b. If yes, how are maintenance recommendations communicated to vehicle operators? c. If yes, who decides whether to implement the MDSS winter maintenance recommendations? d. If no, what software does your state use to process and manage mobile RWIS data?
3.2. Which of the collected mobile RWIS data do you use to decide winter roadway treatments?
3.3. How do your mobile RWIS units communicate with the central DOT server?
3.4. How is your mobile RWIS data integrated with other systems (AVL, GPS, etc.)?
4.1. Provide the estimated costs and savings in your department/district.
4.2. Has your state received any external funding for sensors or software?
4.3. Do you use performance measures to quantify the effectiveness of your winter operations?
5.1. List any of the following implementation challenges experienced in your state/department.
5.2. List any additional challenges experienced in operating mobile RWIS units?
5.3. Does your state have a documented mobile RWIS deployment plan/lessons learned?
6.1. How often do you maintain, clean, calibrate your mobile RWIS units?
6.2. Have you experienced any damages in the wiring of mobile RWIS unit?
6.3. How do you protect mobile RWIS wiring?
7.1. Who uses collected data?
7.2. Where is the collected mobile RWIS data stored?
7.3. How long is collected mobile RWIS data stored?
8.1. Is there any other mobile RWIS information you'd like to share?
8.2. What recommendations/advice can you provide on implementing a new mobile RWIS/MDSS system?

INTERVIEW FEEDBACK AND RESULTS

This section summarizes the findings of the interviews that were conducted to gather feedback from state DOT officials on their experiences utilizing mobile RWIS and MDSS. The finding of the completed interviews are summarized and grouped into the following subsections: (1) background information of mobile RWIS and MDSS use; (2) mobile RWIS hardware and related implementation; (3) mobile RWIS and MDSS software and communications; (4) mobile RWIS and MDSS costs and savings; (5) encountered challenges utilizing mobile RWIS and MDSS; (6) required maintenance for mobile RWIS; (7) mobile RWIS data use, storage, and retention; and (8) additional feedback and comments.

Background Information of Mobile RWIS and MDSS Use

State DOT officials were asked to report how long their state has been using mobile RWIS and MDSS and what is the DOT's official role in their deployment. The collected feedback on the use of mobile RWIS and MDSS is summarized in Table 8. The first year of initial deployment of mobile RWIS and MDSS by the four interviewed state DOTs ranged from 2012 to 2017 and 2001 to 2011, respectively, as shown in Table 8. Note that all four interviewed state DOTs are also members of the FHWA MDSS pooled-fund study and were part of the original development of the MDSS in 2001.

Table 8. Initial Deployment of Mobile RWIS and MDSS

State DOT	First Year of Initial Mobile RWIS Deployment	First Year of MDSS Deployment
Colorado	Pilot: 2015 Operational: 2016	2001
Indiana	2016	2001
Michigan	2012	2011
Minnesota	2017	2007

Mobile RWIS and MDSS Hardware and Related Implementation

State DOT officials were asked to provide feedback on the hardware and implementation of mobile RWIS and MDSS in their state. The feedback provided by interviewed DOT officials is organized and grouped into the following sections: (1) types of mobile RWIS; (2) distribution of mobile RWIS within DOT fleet; (3) mounting of mobile RWIS units; (4) selection of travel routes; (5) coverage of mobile RWIS and MDSS; (6) training provided for mobile RWIS and MDSS; (7) utilization of pre- and post-plow data; and (8) mobile RWIS data integration.

Types of Mobile RWIS

Interviewed DOT personnel were asked to report (1) types of mobile RWIS currently used in their state; (2) types of mobile RWIS units no longer used; (3) factors/reasons for the current selection; and (4) procurement constraints/issues, if any. First, three states (INDOT, MDOT, and MnDOT) reported current use of Lufft MARWIS, two states (MDOT and MnDOT) reported current use of Vaisala MD30, two states (CDOT and MnDOT) reported current use of Teconer RCM411, and one state (MnDOT) reported current use of High Sierra IceSight, RoadWatch, and PreCise, as shown in Table 9.

Second, Colorado was the only state that reported that it discontinued the use of several mobile RWIS units and have continued to use Teconer RCM411 as their preferred mobile RWIS unit since 2016. In contrast, MnDOT continues to use all of its originally procured mobile RWIS units (Lufft MARWIS, Vaisala MD30, High Sierra IceSight, and Teconer RCM411), as shown in Table 9. MnDOT also noted that they started to evaluate the effectiveness of the newer Vaisala MD30 model. MnDOT reported that they utilize both RoadWatch and PreCise ARC wireless road and air temperature units and are moving toward replacing the RoadWatch units with PreCise as they break down.

Third, CDOT stated that the main reason for selecting Teconer RCM411 is its usability, functionality, and ease of integration that were reported by CDOT winter maintenance personnel, as shown in Table 9. They also reported that the collected data by Vaisala was more challenging to integrate into CDOT's system due to the proprietary nature of its system. Fourth, no interviewed state DOT officials reported any procurement issues with obtaining or selecting a single unit mobile RWIS model, as shown in Table 9.

Table 9. Type of Mobile RWIS Used by State DOTs

State DOT	Mobile RWIS Currently Used	Mobile RWIS Discontinued Use	Reasons for Selection	Procurement Issues, if any
Colorado	Teconer RCM411	Lufft MARWIS, Vaisala DSP310, and High Sierra IceSight	Usability, functionality, and ease of integration	No reported issues
Indiana	Lufft MARWIS	None	Wanted single product/model	No reported issues
Michigan	Lufft MARWIS Piloting Vaisala MD30 (2021–2022)	None	Not sure	No reported issues
Minnesota	Lufft MARWIS, Vaisala MD30, High Sierra IceSight, Teconer RCM411, RoadWatch, and PreCise ARC	None	Tested all models	No reported issues

Distribution of Mobile RWIS within DOT Fleet

State DOT officials were asked to provide data on the total number of winter maintenance vehicles in their fleet and the number of these vehicles that are currently equipped with mobile RWIS, as shown in Table 10. The CDOT official reported that 51 of their supervisor vehicles and 7 of their snowplows are equipped with mobile RWIS. This represents approximately 80% and 1% of their supervisor vehicles and snowplows, respectively. The INDOT official reported they utilize a flexible approach that allows the districts to decide the deployment needs of their 29 mobile RWIS units, and they allow districts to split them between supervisor vehicles and snowplows. The MDOT official reported they deploy one Vaisala MD30 each on a supervisor vehicle and a snowplow. Additionally, all 330 of their snowplows have RoadWatch units. The MnDOT official reported they deploy 3 to 4 mobile RWIS units on supervisor vehicles, 10 mobile RWIS units on snowplows, and 800 road and pavement temperature sensors (RoadWatch or PreCise ARC System) on snowplows, as shown in Table 10.

Table 10. Number of Vehicles in DOT Fleet and Number of Vehicles Equipped with Mobile RWIS

State DOT	Total Number of Supervisor Vehicles in Fleet	Total Number of Snowplows in Fleet	Number of Supervisor Vehicles with Mobile RWIS	Mobile RWIS Model	Number of Snowplow with Mobile RWIS	Mobile RWIS Model
Colorado	65	900	51	Teconer RCM411	7	Teconer RCM411
Indiana	200	1105	29 (Split between supervisor and snowplows)	Lufft MARWIS	29 (Split between supervisor and snowplows)	Lufft MARWIS
Michigan	Unknown	330	1	Vaisala MD30	330 1	RoadWatch Vaisala MD30
Minnesota	Unknown	850	3–4	Various	800 10	RoadWatch or PreCise ARC Various

Mounting of Mobile RWIS Units

Interviewed DOT officials were asked to provide details on the mounting and installation of mobile RWIS units on supervisor vehicles and snowplows, as shown in Table 11 and Table 12, respectively. For supervisor vehicles, the reported mounting locations recommended by mobile RWIS manufacturers include trailer hitch, rear mounted, front bumper mounted, and roof mounted. Each of these mounting locations require unique mounting types such as trailer hitch insert, magnetic mount, drilling directly into the front bumper, or custom-made brackets, as shown in Table 11. No interviewed state DOTs reported issues with their current mounting locations. MnDOT, however, reported they have tested and discontinued a variety of mounting locations in the past including the underbody mount due to the mobile RWIS sensor being obstructed with snow. This mounting location was replaced by MnDOT with a custom-made bracket to switch to a roof-mounted location, as shown in Table 11.

Table 11. Mounting Locations of Mobile RWIS on Supervisor (Light-Duty) Vehicles

State DOT	Mounting Location	Type of Mount	Issues with Mounting	Solutions for Mounting, if any
Colorado	Trailer Hitch	Trailer Hitch Insert	No reported issues	N/A
Indiana	Rear	Magnetic or Trailer Hitch Insert	No reported issues	N/A
Michigan	Front Bumper	Drilled into Front Bumper	No reported issues	N/A
Minnesota	Teconer: Front Bumper High Sierra: Roof	Teconer: Drilled into Front Bumper High Sierra: MnDOT-made Bracket	Tested different mounting locations and discontinued underbody mount due to snow obstructing sensors	Utilize different mounting location

For snowplows, the reported mounting locations include (1) directly behind the plow on the front bumper, which was reported by three state DOTs (Colorado, Michigan, and Minnesota), and (2) truck frame between the driver's cabin and truck bed in front of the tandem snowplow, which was reported by INDOT, as shown in Table 12. No interviewed state DOT reported issues with their current mounting locations. MnDOT, however, reported they have tested and discontinued mounting on the truck frame behind the driver's cabin in the past and experienced snow and debris obstructions with the mobile RWIS unit, as shown in Table 12. After the conducted interview, MnDOT personnel provided additional images of their mounted units on both supervisor vehicles and snowplows, as shown in Figure 17.

Table 12. Mounting Locations of Mobile RWIS on Snowplows (Heavy-Duty) Vehicles

State DOT	Mounting Location	Type of Mount	Issues with Mounting	Solutions for Mounting, if any
Colorado	Large behind plow on front bumper	Attached to front bumper	No reported issues	N/A
Indiana	Between cab and truck bed, on truck frame in front of tandem snowplow	Manufacturer custom-made bracket	No reported issues	N/A
Michigan	Behind plow	Attached to front bumper	No reported issues	N/A
Minnesota	Behind plow	MnDOT-made bracket	Tried to mount behind cab, obstructed sensor with snow and debris	Utilize different mounting location

(a) Mobile RWIS mounted on supervisor vehicle

(b) Close up of magnetic mount on supervisor vehicle

(c) Mobile RWIS mounted on front bumper of snowplow

Figure 17. Photo. Mobile RWIS mounting configurations on MnDOT vehicles.

Selection of Travel Routes

State DOTs were asked to report the criteria for selecting travel routes for vehicles equipped with mobile RWIS units. All interviewed DOT personnel reported that interest/support from DOT maintenance staff was extremely important to the viability of mobile RWIS usage, as shown in Table 13. Three state DOTs (Colorado, Indiana, and Minnesota) reported that high ADT roadways was a top-ranking criterion in determining mobile RWIS deployment. Additional criteria used to select travel routes for vehicles equipped with mobile RWIS include problem areas, identified gaps of fixed RWIS sites, validation of data from fixed RWIS sites, and distribution equity among districts, as shown in Table 13.

Table 13. Criteria for Selecting Travel Routes for Vehicles with Mobile RWIS

State DOT	Criteria
Colorado	Primary focus is interstate highways and high priority areas/corridors that need constant deicing. Secondary focus is support/interest from management and plow drivers.
Indiana	Initial deployment was to gain interest from INDOT personnel and to fill gaps of fixed RWIS stations. Further deployments have been equally distributed among districts, deployed on a mix of interstate and rural routes.
Michigan	Primary criterion was participation from MDOT personnel. Secondary criterion was to validate data from fixed RWIS sites.
Minnesota	Primary focus is busy roadways and equipping trucks that are used on all shifts. Secondary focus is obtaining feedback from MnDOT maintenance personnel. Additional criteria: fill gaps of fixed RWIS, and areas with historic winter problems.

Coverage of Mobile RWIS and MDSS

Interviewed DOT officials were asked to report their current coverage of mobile RWIS and MDSS and their planned expansion, if any. CDOT reported that approximately 80% of their supervisor vehicles and 1% of their snowplows are equipped with mobile RWIS. CDOT also reported that their MDSS coverage is statewide, and it is higher in densely populated areas, as shown in Table 14. INDOT reported that mobile RWIS coverage is left up to the districts and that districts have the flexibility to switch the use of their mobile RWIS units between supervisor vehicles and snowplows. INDOT also reported that their MDSS coverage is significant. MDOT reported they are currently conducting a mobile RWIS pilot study with one mobile RWIS unit each on a supervisor vehicle and a snowplow. MDOT also noted that approximately 20%–25% of their routes are covered by MDSS. MnDOT reported that three to four of their supervisor vehicles have mobile RWIS units, 90%–95% of their trucks have road and air temperature sensors, and 1%–3% of their trucks have mobile RWIS units. MnDOT also stated that every route can be covered by MDSS; however, only 85% of trucks are equipped with MDSS displays.

Two state DOTs (Colorado and Minnesota) reported they have no current plans to expand their mobile RWIS program. CDOT noted their current goal is to maximize/optimize the use of its existing sensors. MnDOT reported that future expansion would be based on the need to collect data in areas with limited fixed RWIS coverage. MnDOT is currently constructing 70–80 fixed RWIS sites at approximately $70,000 each to reduce the number and size of its data collection gaps. Two states DOTs (Indiana and Michigan) are currently conducting studies that have the potential to increase the mobile RWIS coverage but are still awaiting results. All four states reported there are no current plans for expanding their MDSS coverage, as shown in Table 14.

Table 14. Current Coverage and Planned Expansion of Mobile RWIS and MDSS

State DOT	Current Coverage	Planned Expansion
Colorado Mobile RWIS	Approximately 80% of supervisor vehicles and 1% of snowplows.	No planned expansion and goal is to maximize/optimize the use of existing sensors.
Colorado MDSS	MDSS has statewide coverage, and it is higher in densely populated areas.	No planned expansion.
Indiana Mobile RWIS	Mobile RWIS coverage is determined by district, 29 units are switched between supervisor vehicles and snowplows.	Currently researching "smart snowplow" with mobile sensors, automated spreader function, etc. Based on results, there is potential to deploy mobile RWIS on all snowplows.
Indiana MDSS	MDSS has significant coverage.	No planned expansion.
Michigan Mobile RWIS	Mobile RWIS pilot study is ongoing, one mobile RWIS on supervisor vehicle and one on snowplow.	Future expansion will depend on pilot project findings, mobile RWIS cost, and benefits.
Michigan MDSS	Approximately 20%–25% of routes covered by MDSS.	No planned expansion.
Minnesota Mobile RWIS	Approximately 3–4 supervisor vehicles have mobile RWIS sensors. Approximately 90%–95% of trucks have road and air temperature sensors. Approximately 1%–3% of trucks have comprehensive mobile RWIS.	Future expansion based on collected data of RWIS gaps. Currently constructing 70–80 fixed RWIS sites at $70k per site, which reduces the number and size of gaps.
Minnesota MDSS	MDSS coverage is significant, every route can be covered, approximately 80%–85% of trucks have MDSS displays.	No planned expansion.

Training Provided for Mobile RWIS/MDSS

State DOT officials were asked to report feedback on the offered training programs for their maintenance personnel for mobile RWIS and MDSS. All four interviewed state DOTs reported that mobile RWIS and MDSS are included within their state's winter operations preparation training conducted each fall, as shown in Table 15. All four interviewed state DOTs also reported they utilized the training provided by mobile RWIS and MDSS vendors. Furthermore, CDOT reported they have experienced more support from their maintenance personnel by having a CDOT lead that can be used as a resource to answer questions as well as provide training, manuals, and help with integrating mobile RWIS and MDSS into vehicles. MDOT utilizes a mix of virtual synchronous training modules and recorded asynchronous training modules that can be accessed by maintenance staff as needed, as shown in Table 15.

Table 15. Training Provided for Mobile RWIS and MDSS

State DOT	Winter Prep Training	Vendor Provided	Additional Training Comments
Colorado	✓	✓	There is a CDOT lead contact to answer questions, provide additional training, manuals, and help with integration. Received a lot more support from CDOT personnel when they are able to ask an experienced CDOT person instead of having to contact vendor every time with a question/comment.
Indiana	✓	✓	Yearly refreshers for managers and supervisors are provided by INDOT and vendors.
Michigan	✓	✓	Utilized MDSS since 2013, training is very structured, week or so of yearly training on MDSS/AVL with vendor. Mix of virtual and recorded training.
Minnesota	✓	✓	MnDOT has a training website (iHUB) for training videos, manuals, and refreshers. Individual training can be requested. Yearly refresher provided by vendor.

Utilization of Pre-Plowed and Post-Plowed Data

Interviewed DOT officials were asked to report how they utilize pre-plow and post-plow data provided by mobile RWIS and MDSS. All four state DOTs reported that plow drivers have access to real-time data within the vehicle either through the MDSS, snowplow spreader controls, or through a stand-alone display unit, as shown in Table 16. Three state DOTs (Colorado, Indiana, and Minnesota) reported that their maintenance personnel can access MDSS data through a computer web-based application. MDOT reported they can save storm data for future review or for use as a teaching / training tool. Otherwise, their storm data is stored for 72 hours, as shown in Table 16.

Table 16. Utilization of Pre-Plowed and Post-Plowed Data

State DOT	Pre-Plowed and Post-Plowed Data Users
Colorado	Plow operators receive real-time data in vehicle. Supervisors and managers are able to view current and past data. Post storm analysis not really used.
Indiana	Plow operators receive real-time data in vehicle. Data can also be accessed through Lufft View Mondo software.
Michigan	Plow operators have in-vehicle displays for MDSS, currently trying to integrate tablets. System saves 72 hours of road and weather data including recommended treatments vs actual. Storm data can be saved for review or teaching tools.
Minnesota	Plow operators receive MDSS recommendations through in-vehicle display. Maintenance personnel can access data through computer from maintenance shed.

Mobile RWIS Data Integration

DOT representatives were asked to report if their mobile RWIS data is integrated into road condition reports that are released to the public. All four state DOT officials reported that mobile RWIS data is for internal DOT use only and is not integrated into public traveler information system, as shown in Table 17. Two state DOTs (Indiana and Michigan) reported that public road and weather information systems are updated with fixed RWIS data, weather data from other sources, traffic data, and camera images that allow the public to see the current roadway conditions. MnDOT reported that their 511 traveler information system is updated manually by MnDOT personnel and then released to the public. As of last winter season, MnDOT has started to link MDSS data to the public site along with camera images from snowplows. This system is currently being tested to ensure the accuracy of data shared with the public, as shown in Table 17.

Table 17. Mobile RWIS Data Integration into Public Site

State DOT	Mobile RWIS Data Integration	Additional Comments
Colorado	No	Mobile RWIS data is internal for CDOT use.
Indiana	No	Data from fixed RWIS sites, traffic, and snowplow cameras are integrated into the traveler information system.
Michigan	No	Fixed RWIS sites data, weather data from other sources, and camera images are integrated into traveler information system.
Minnesota	No	Public road and weather information system (511) is updated manually by MnDOT. Starting last winter season, road and weather information is being linked to MDSS then to 511 traveler's information system along with camera images from trucks. This automated system is under testing to ensure the accuracy of data shared with the public.

Mobile RWIS and MDSS Software and Communications

State DOT officials were asked to report their mobile RWIS and MDSS software and communication pathway used in their state. Their collected feedback is organized and grouped into the following four sections: (1) utilization of MDSS; (2) collected mobile RWIS data; (3) communication pathway of mobile RWIS units; and (4) integration of mobile RWIS data with other systems.

MDSS Utilization

Interviewed DOT personnel were asked to provide feedback on their utilized mobile RWIS software as well as their use of MDSS including its software, procedure for communicating MDSS recommendations to plow operators, and procedure for making decisions on winter maintenance treatment. Interviewed state DOT officials reported they use a variety of mobile RWIS software including Teconer's web-accessed database and Lufft View Mondo, as shown in Table 18. All state DOTs reported they utilize MDSS and use Data Transmission Network (DTN) as the vendor for the MDSS software, as shown in Table 18. Three state DOTs (Indiana, Michigan, and Minnesota) reported that their snowplow operators receive MDSS recommendations in the vehicle displays. CDOT reported that their snowplow operators decide treatment on their own without receiving MDSS treatment recommendations. For other states that provide operators with in-vehicle MDSS treatment recommendations, the final decision to apply treatment is ultimately left up to the snowplow operator, as shown in Table 18. MDOT reported that the maintenance supervisor rarely directs the plow operators to utilize the MDSS recommendations. MnDOT snowplow operators also decide the final treatment and whether to utilize the MDSS recommendation; however, MnDOT operators can also respond back to MDSS/DTN when disagreeing with the recommendation to indicate any inconsistencies with the provided forecast. For example, the operator can report the inaccuracy of the MDSS forecast and recommendations in cases where the actual road and weather conditions are different from those provided by the MDSS.

Table 18. Utilization of MDSS and Mobile RWIS Software

State DOT	Used Mobile RWIS Software	Use of MDSS	Used MDSS Software	Method of MDSS Communication to Snowplows	Decision Maker of Maintenance Treatment
Colorado	Teconer Database	Yes	DTN	Plow operators do not receive in-vehicle MDSS recommendations	Plow operators make treatment decisions without MDSS recommendation
Indiana	Lufft View Mondo	Yes	DTN	Plow operators receive in-vehicle MDSS recommendations	Plow operators make treatment decisions
Michigan	N/A	Yes	DTN	Plow operators receive in-vehicle MDSS recommendations	Plow operators make treatment decisions
Minnesota	Plow operators see mobile RWIS data in-vehicle	Yes	DTN	Plow operators receive in-vehicle MDSS recommendations	Plow operators make treatment decisions

Collected Mobile RWIS Data

DOT officials were asked to report the road and weather parameters used in their states to determine winter roadway treatments. Two state DOTs (Colorado and Michigan) reported that friction is one of the most important parameters for determining winter roadway treatment, as shown in Table 19. CDOT reported that friction below 0.5 requires treatment, and that this friction threshold is often lower in metropolitan areas. MnDOT reported they do not have standards that specify roadway parameter thresholds for winter roadway treatment. Instead, MnDOT provides the operators with the flexibility to use their judgement to apply winter roadway treatment based on their on-site observations and road parameters such as calculated friction or grip, as shown in Table 19.

Table 19. Road and Weather Parameters Used to Determine Winter Roadway Treatment

State DOT	Parameters Used in Deciding Winter Roadway Treatment
Colorado	Friction below 0.5 requires treatment. Lower tolerance in metro areas.
Indiana	No reported parameters.
Michigan	Friction and grip are most important.
Minnesota	All road and weather parameters are collected. Overall winter treatment strategy is not determined by a single parameter such as grip or calculated friction, but snowplow operators can use these parameters in their decision making.

Type of Mobile RWIS Communication with DOT Server

Interviewed DOT personnel were asked to report the communication methods on their mobile RWIS units utilized in their states. All four state DOTs reported they use cellular networks to collect data from their mobile RWIS units, as shown in Table 20. CDOT reported that their Teconer units communicate to their in-vehicle phones via Bluetooth and then utilize cellular data to send data to the Teconer database.

Table 20. Communication Methods of Mobile RWIS

State DOT	Communication Method Between Mobile RWIS and Central DOT Server
Colorado	Bluetooth from mobile RWIS unit to phone, then cellular to Teconer database
Indiana	Cellular
Michigan	Cellular
Minnesota	Cellular

Mobile RWIS Data Integration with Other Systems

State DOTs officials were asked to report how their state integrates mobile RWIS data with other systems (e.g., AVL, MDSS, etc.). All four states reported they do not integrate mobile RWIS data into other systems, as shown in Table 21. A representative from DTN confirmed that MDSS currently does not integrate mobile RWIS data into MDSS treatment recommendations or road weather forecasts.

Table 21. Mobile RWIS Data Integration with Other Systems

State DOT	Mobile RWIS Data Integration with Other Systems
Colorado	Mobile RWIS data not integrated into other systems
Indiana	Mobile RWIS data not integrated into other systems
Michigan	Mobile RWIS data not integrated into other systems
Minnesota	Mobile RWIS data not integrated into other systems

Mobile RWIS and MDSS Costs and Savings

State DOT officials were asked to report the mobile RWIS and MDSS costs and savings experienced in their states. Their collected feedback is organized and grouped into the following three sections: (1)

mobile RWIS and MDSS costs and savings; (2) external funding received for mobile RWIS or MDSS; and (3) performance metrics used to quantify the effectiveness of winter maintenance operations.

Mobile RWIS and MDSS Costs and Savings

Interviewed DOT personnel were asked to report mobile RWIS and MDSS costs and savings experienced in their states, as shown in Table 22 and Table 23, respectively. First, mobile RWIS costs and savings were reported by two interviewed officials (Colorado and Minnesota). For example, CDOT reported they spend approximately $40 per month per unit. CDOT also noted they have spent an additional $15,000 to support their mobile RWIS program for spare parts such as phones, wiring, harnesses, and brackets. CDOT has not conducted a formal cost-benefit analysis but reported that districts that have utilized mobile RWIS units anecdotally reported an approximate 20% decrease in material usage and therefore requested additional mobile RWIS units. Three state DOTs (Indiana, Michigan, and Minnesota) have not conducted studies to analyze the costs or savings of mobile RWIS, as shown in Table 22. MnDOT provided additional cost and savings data after the interview that reported the use of mobile RWIS and MDSS in 11 winter events in 2010 enabled it to achieve an average of 53% reduction in salt usage and cost savings of $2,308,866, as shown in Table 22.

Table 22. Mobile RWIS Costs and Savings

State DOT	Operations and Maintenance Costs	Realized Cost Savings	Additional Benefits
Colorado	Data plan $40/month Approximately $15,000 spare parts, phones, etc.	Approximately 20% decrease in material usage	Decreased material usage
Indiana	Not reported	Not reported	Not reported
Michigan	Not reported	Not reported	Not reported
Minnesota	Not reported	$2,308,866 material cost savings in 2010	53% less material used on roadways

Second, MDSS costs and savings were reported by two interviewed officials (Colorado and Minnesota). For example, CDOT reported an MDSS software operational cost of approximately $600,000 per year to cover their routes, as shown in Table 23. CDOT noted that the cost savings was difficult to quantify due to the lack of formal studies conducted; however, the CDOT official reported that MDSS recommendations have been used as a training tool for newer plow operators that may not be as familiar with winter roadway treatments. MDOT was not able to report any costs or savings but noted that an additional benefit of MDSS is that the forecasts help identify manpower needs for upcoming storms. MnDOT reported the costs for AVL systems in each truck to be approximately $1,200 to $1,400. MnDOT provided additional cost and savings data after the interview that reported that the use of mobile RWIS and MDSS in 11 winter events in 2010 enabled it to achieve an average of 53% reduction in salt usage and cost savings of $2,308,866, as shown in Table 23.

Table 23. MDSS Costs and Savings

State DOT	Operations and Maintenance Costs	Realized Cost Savings	Additional Benefits
Colorado	$600,000 per year	Not reported	Good training and preparation tool for new plow operators Decreased material usage
Indiana	Not reported	Not reported	Not reported
Michigan	Not reported	Not reported	Help identify manpower needs based on forecast
Minnesota	AVL systems in trucks cost $1,200–$1,400 per vehicle	$2,308,866 material cost savings in 2010	53% less material used on roadways

External Funding Received

Interviewed DOT personnel were asked to report if they have received any external funding for mobile RWIS or related software. CDOT obtained FHWA funding through a State Transportation Innovation Council incentive program to deploy a handful of mobile RWIS units, as shown in Table 24. INDOT reported federal match of some funds as part of the FHWA pooled-fund study. The INDOT official also noted that grant opportunities do exist for mobile RWIS sensors and/or software. MnDOT reported receiving FHWA funding as part of the IMO project, as shown in Table 24.

Table 24. External Funding Received for Mobile RWIS or Software

State DOT	External Funding Received
Colorado	State Transportation Innovation Council grant for a few mobile RWIS units
Indiana	Pooled Fund Study received Federal match
Michigan	No external funding
Minnesota	FHWA Integrated Mobile Observations project funding

Performance Measures Used to Quantify Effectiveness of Winter Maintenance

State DOTs were asked to report the performance measures used to quantify the effectiveness of winter maintenance operations in their states. All states reported that they utilize level-of-service (LOS) classifications for their roadways that range from two to five levels, where each classification requires different performance measures for winter maintenance operations, as shown in Table 25. For example, MDOT utilizes two levels of service classification (orange and blue routes) and specifies the performance measure for its orange and blue routes to be “pavement surface over its entire width be generally bare of ice and snow,” and “pavement surface be generally bare of ice and snow wide enough for one-wheel track in each direction,” respectively. Similarly, MnDOT utilizes the “bare-lane classification” as their performance measure, which states that “all driving lanes are free of snow and ice between the outer edges of the wheel paths and have less than 1 inch of accumulation on the center of the roadway.” For Minnesota roadways, the five LOS classifications (super commuter, urban commuter, rural commuter, primary, and secondary) determines the allowable time to regain the bare lane. For example, super commuter roadways should be cleared in 0 to 3 hours, while secondary roadways should be cleared in 9 to 36 hours, as shown in Table 25.

Table 25. Performance Measures Used to Quantify the Effectiveness of Winter Maintenance

State DOT	Level of Service Classification	Performance Measure
Colorado	Five levels: A	Maintain wet (bare) pavement throughout a storm on higher-standard or highly travelled highways to snow-pack or icy but passable conditions on lower-standard or low-volume roads.
Colorado	B	Maintain wet (bare) pavement as much as possible on higher-standard or highly travelled highways to snow-pack or icy conditions on lower-standard or low-volume roads.
Colorado	C	Maintain wet (bare) pavement as much as possible to patches of snow or slush. On lower-standard or low volume roads LOS "C" ranges from patches of snow or ice to predominately snow-pack or icy conditions.
Colorado	D	Patches of "oatmeal" snow, packed snow, or ice on higher-standard or highly travelled highways to predominately snow-packed or icy conditions on lower-standard or low-volume roads.
Colorado	F	Patches of snow or ice exist even on the highest-standard roads, and these conditions may degenerate to predominately snow-packed or icy conditions throughout with accompanying slowdowns or delays.
Indiana	Three levels: Class I, II, and III	Under development.
Michigan	Two levels: Orange Routes	Pavement surface over its entire width be generally bare of ice and snow.
Michigan	Blue Routes	Pavement surface be generally bare of ice and snow and wide enough for one-wheel track in each direction.
Minnesota	Five levels: Super Commuter	Bare Lane Classification: All driving lanes are free of snow and ice between the outer edges of the wheel paths and have less than 1 inch of accumulation on the center of the roadway. Bare lane regained in 0–3 hours.
Minnesota	Urban Commuter	Bare lane regained in 2–5 hours.
Minnesota	Rural Commuter	Bare lane regained in 4–9 hours.
Minnesota	Primary	Bare lane regained in 6–12 hours.
Minnesota	Secondary	Bare lane regained in 9–36 hours.

Encountered Challenges Utilizing Mobile RWIS and MDSS

State DOT officials were asked to report the challenges encountered in their states while utilizing mobile RWIS and MDSS. Their collected feedback is organized and grouped into the following three sections: (1) implementation challenges such as installation, operational, and user/personnel challenges; (2) additional challenges; and (3) mobile RWIS pilot/deployment plan.

Implementation Challenges

Interviewed DOT personnel were asked to report the mobile RWIS and MDSS implementation challenges encountered such as installation, operational, and user/personnel challenges, as shown in Table 26 and Table 27. No state DOTs reported any installation challenges with mobile RWIS units, as shown in Table 26. CDOT reported they have experienced wire corrosion at the rear of the mobile RWIS unit. Additionally, CDOT reported several personnel challenges including high turnover rates, varying levels of interest in mobile RWIS, and different goals between operators and supervisors. Similarly, INDOT reported that it took time for some maintenance personnel to see the value in mobile RWIS due to their reluctance to new systems, as shown in Table 26.

Table 26. Challenges Encountered Using Mobile RWIS

State DOT	Installation Challenges	Operational Challenges	User/Personnel Challenges
Colorado	No reported challenges	Wire corrosion at the rear of sensor	Turnover, levels of interest, different goals, etc.
Indiana	No reported challenges	No reported challenges	Maintenance personnel are resistant to change
Michigan	No reported challenges	No reported challenges	No reported challenges
Minnesota	No reported challenges	No reported challenges	No reported challenges

Interviewed DOT officials were also asked to report their encountered MDSS implementation challenges including installation, operational, and user/personnel challenges. Two state DOTs (Colorado and Minnesota) reported installation challenges caused by changes in MDSS interface and data feeds in newer installations, as shown in Table 27. CDOT reported that ensuring access for its 1,500+ maintenance staff is an operational challenge. MDOT reported there are occasional operational issues such as data having to be modified or "scrubbed" before release to avoid inaccurate data. CDOT noted that their encountered personnel challenges included high turnover rates, varying levels of interest, and ensuring software is operational. INDOT stated that MDSS provides a forecast and treatment recommendation; however, forecasts can be inaccurate, causing maintenance personnel to be reluctant to use the system, as shown in Table 27.

Table 27. Challenges Encountered Using MDSS

State DOT	Installation Challenges	Operational Challenges	User/Personnel Challenges
Colorado	Changes in MDSS interface and data feeds	Making sure people have access (1,500+ people)	Turnover, levels of interest, ensuring software is working
Indiana	No reported challenges	No reported challenges	MDSS provides a forecast which can be inaccurate at times, causing operators to be reluctant to use
Michigan	No reported challenges	Occasional issues such as modifying/scrubbing data before release	No reported challenges
Minnesota	Changes in MDSS interface and data feeds	No reported challenges	No reported challenges

Additional Challenges

State DOT officials were asked to report any additional challenges encountered utilizing mobile RWIS and MDSS. CDOT reported that collected mobile RWIS data often needs to be reviewed to ensure accuracy, as shown in Table 28. INDOT reported some issues with INDOT personnel not calibrating mobile RWIS units regularly, but overall they reported that the mobile RWIS units work well. MDOT reported they have experienced issues with older mobile RWIS units, as some of these units may need to be replaced after eight years/seasons, as shown in Table 28.

Table 28. Additional Challenges

State DOT	Additional Challenges
Colorado	Collected mobile RWIS data needs to be reviewed to ensure accuracy
Indiana	Reminding personnel to calibrate mobile RWIS units regularly
Michigan	Issues with older models (8+ years) that may need replacement
Minnesota	No reported challenges

Mobile RWIS Deployment Plan

Interviewed DOT personnel were asked if they had a mobile RWIS pilot/deployment plan that could be shared. No state DOTs had a documented mobile RWIS pilot project deployment plan, as shown in Table 29.

Table 29. Mobile RWIS Deployment Plan

State DOT	Deployment Plan
Colorado	None available
Indiana	None available
Michigan	None available
Minnesota	None available

Required Maintenance for Mobile RWIS

State DOT officials were asked to report their mobile RWIS maintenance and any experienced damage to wiring of mobile RWIS units. The collected feedback in this section is organized and grouped into the following two subsections: maintenance frequency of mobile RWIS and experienced damage to wiring.

Maintenance Frequency of Mobile RWIS

State DOT personnel were asked to report the frequency that their state conducts maintenance on mobile RWIS units. All four state DOTs reported they regularly check their mobile RWIS units for maintenance before or after winter events, as shown in Table 30. Two state DOTs (Colorado and Minnesota) reported that calibration is performed as needed, while two other state DOTs (Indiana and Michigan) reported they have scheduled calibration for mobile RWIS units.

Table 30. Maintenance Frequency of Mobile RWIS

State DOT	Maintenance Frequency
Colorado	Clean mobile RWIS unit at end of shift and calibrate units as needed.
Indiana	Avoid damaging units when power washing truck and calibrate every year.
Michigan	Clean, calibrate and perform maintenance every time truck is washed.
Minnesota	Clean mobile RWIS units after every snowstorm and protect sensor when power washing the truck. Check units at beginning of winter event and calibrate units as needed.

Experienced Damage to Wiring

Interviewed DOT officials were asked to report if they have experienced any damage to the wiring of mobile RWIS units and if they utilize any wiring protection to prevent this damage, as shown in Table 31. Two state DOTs (Colorado and Michigan) reported they have experienced damage to the wiring of mobile RWIS units. CDOT utilizes replacement parts as needed and/or applies dielectric grease to repel moisture and protect electrical connections against corrosion, as shown in Table 31.

Table 31. Damage to Wiring of Mobile RWIS

State DOT	Damage to Wiring of Mobile RWIS	Mobile RWIS Wiring Protection, if any
Colorado	Wire corrosion at sensor and on wiring harnesses	Utilize replacement parts and/or dielectric grease
Indiana	No reported issues	No reported protection
Michigan	Damaged wiring in 5%–10% units	No reported protection
Minnesota	No reported issues	No reported protection

Mobile RWIS Data Use, Storage, and Retention

State DOT officials were asked to report their states' mobile RWIS and MDSS data use, storage, and retention. The collected feedback is organized and grouped into the following two sections: users of collected road and weather data as well as location and duration of collected data.

Users of Collected Road and Weather Data

Interviewed DOT personnel were asked to report the users of the collected road and weather data. Two state DOTs (Colorado and Minnesota) reported that their plow operators see the mobile RWIS data through an in-vehicle display, as shown in Table 32. Two other state DOTs (Indiana and Michigan) reported that their snowplow operators receive the MDSS recommendations through the in-vehicle display, but not the real-time weather data. Colorado and Indiana DOTs also reported the ability to access the collected road and weather data through web-based computer software. MDOT sends all collected data to MDSS software vendor DTN and then distributes the data from DTN to FTP sites for various uses, including traveler information systems, DOT-related information, and research, as shown in Table 32.

Table 32. Users of Collected Road and Weather Data

State DOT	Users of Collected Data
Colorado	Snowplow operator Managers/Supervisors have access to MDSS and mobile RWIS data
Indiana	Field managers, directors, and maintenance garage supervisors can view data through Lufft View Mondo software
Michigan	All AVL and road weather data is sent to DTN. FTP sites are then used to distribute data to several users such as public travel information, DOT, research, etc.
Minnesota	Snowplow operator

Location and Duration of Storing Collected Data

DOT officials were asked to report the location and duration of storing the collected road and weather data, as shown in Table 33. CDOT stores data on the Teconer database, INDOT stores data in a centralized INDOT data warehouse, and MDOT and MnDOT store data by the MDSS vendor DTN. The duration of storing collected data also varied between state DOTs, as shown in Table 33. CDOT reported that their collected data is stored forever. MDOT reported storing MDSS and mobile RWIS data for 72 hours and 14 days, respectively. MnDOT reported storing storm data for two years but was unsure on the duration of storing mobile RWIS data, as shown in Table 33.

Table 33. Location and Duration of Storing Collected Data

State DOT	Location of Collected Data	Duration of Storing Collected Data
Colorado	Stored on Teconer server	Forever
Indiana	INDOT central data warehouse	Not sure on duration of data retention
Michigan	Stored by MDSS vendor	MDSS is stored 72 hours. RWIS data is stored for 14 days
Minnesota	Stored by MDSS vendor	Storm data is stored for two years. Not sure about mobile data

Additional Feedback on Mobile RWIS and MDSS

At the end of the interview, DOT officials were asked to provide any additional feedback on mobile RWIS and MDSS. Their collected feedback is organized and grouped into the following two sections: additional information on mobile RWIS and recommendations for implemented new mobile RWIS / MDSS system.

Additional Information on Mobile RWIS

State DOT personnel were asked to provide any additional information on mobile RWIS, as shown in Table 34. Both CDOT and INDOT reported the potential of significant benefits that can be realized by utilizing mobile RWIS for winter maintenance operations. CDOT further elaborated that mobile RWIS can be more valuable than MDSS to snowplow operators. Additionally, CDOT reported that the cost of a mobile RWIS unit is insignificant compared to the cost of a snowplow, as shown in Table 34.

Table 34. Additional Information on Mobile RWIS

State DOT	Additional Information
Colorado	Potential of significant benefits that can be realized by utilizing mobile RWIS for winter maintenance operations. MDSS provides recommendation/forecast, but mobile RWIS data is real time, which has more value. Equipping a $250–300k plow with an 8k sensor to perform better makes sense.
Indiana	Potential of significant benefits that can be realized by utilizing mobile RWIS for winter maintenance operations.
Michigan	No additional comments.
Minnesota	No additional comments.

Recommendations or Advice for Implementing Mobile RWIS and MDSS System

Interviewed DOT officials were asked to provide any recommendations or advice for implementing mobile RWIS and MDSS system. CDOT recommended starting small in a single district or division in order to refine and improve the system, as shown in Table 35. CDOT noted that a localized efficient system builds support from the district maintenance staff, which can be used as an example for statewide implementation. Additionally, CDOT recommended deploying more mobile RWIS units on snowplows rather than supervisor vehicles, as they recommended allocating 75% of the available units to snowplows to improve the efficiency of winter maintenance operations. INDOT reported that MDSS is significantly better than traditional forecasts. For example, the National Weather Service may report 6 inches of snowfall, but that does not provide adequate information on pavement and traffic conditions, whether snow is packed, blown into loose piles on the roadway, or blown off the road completely. MDOT reported that internal DOT support was extremely important and highlighted the need for communicating the benefits of mobile RWIS and MDSS to maintenance personnel and how they can support them in improving the performance of their jobs, as shown in Table 35.

Table 35. Recommendations for Implementing Mobile RWIS and MDSS

State DOT	Recommendations for Mobile RWIS and MDSS Implementation
Colorado	Start small in a single district or division, refine the system to achieve local support, and then use that district as an example to expand statewide. Figure out the main goals before committing to the system, such as public road and travel information, improving material management, improving level of service. Would recommend allocating more mobile RWIS units on snowplows (75%) than supervisor vehicles (25%) unless supervisor is always patrolling every time it snows.
Indiana	MDSS is meant for road weather forecasting. National Weather Service may report six inches of snow, but that may look very different on the pavement as it can be packed down by vehicles, loose, or blown off by wind.
Michigan	Communicate the benefits of mobile RWIS and MDSS to maintenance personnel and how they can support them in improving the performance of their jobs.
Minnesota	Reach out to other state DOTs for their best practices, techniques, and mobile RWIS units.

CHAPTER 4: RECOMMENDATIONS FOR PILOT STUDY DEPLOYMENT

This chapter provides recommendations that can be used by IDOT to conduct a pilot study to evaluate the deployment and performance of mobile RWIS and MDSS in order to determine their effectiveness, implementation requirements, software/technology needs, operational challenges, and life-cycle costs. This proposed pilot study was developed based on the main findings of the research tasks in Chapters 2 and 3. The proposed study is organized into the following sections: research objectives, research tasks and methodology, schedule, and estimated equipment and software budget.

RESEARCH OBJECTIVE

The main goal of this proposed research project is to conduct a pilot study to evaluate the effectiveness of integrating mobile RWIS and MDSS into existing IDOT winter maintenance operations. To accomplish this goal, the research objectives of this project are as follows:

1. Identify potential districts, routes, vehicles, and personnel that will participate in the pilot study based on several criteria, including areas with gaps in fixed RWIS coverage; roads with high average daily traffic such as interstate highways; locations with history of blowing snow and/or icy roads; locations with high rate of winter weather-related crashes; and districts with high level of interest from maintenance personnel.

2. Install mobile RWIS units and MDSS display units on selected plows and supervisor vehicles that were identified in the previous task, which will be implemented in a number of subtasks that will focus on (a) selecting and acquiring 12 mobile RWIS units developed by 3 manufacturers and were reported to be used by other state DOTs, (b) acquiring MDSS display units and video cameras for all vehicles that will be equipped with mobile RWIS units, (c) mounting and calibrating mobile RWIS units and MDSS displays on participating vehicles, and (d) providing training to winter maintenance operations personnel on the use of mobile RWIS units and MDSS.

3. Conduct the first phase of the pilot study to evaluate the effectiveness of currently utilized and the 12 newly purchased mobile RWIS units and MDSS during the first winter season and to provide recommendations for improving their performance in the second winter season of the project. The planned research work in this task is organized into the following two subtasks:

   3.1 Collect all data generated by mobile RWIS and MDSS during the first winter season including data on (a) capabilities of different mobile RWIS models in collecting various road and weather data such as road condition, road surface temperature, water film height, ice percentage, friction, ambient air temperature, and relative humidity; (b) performance and reliability of different mobile RWIS units in providing uninterrupted and accurate road and weather data measurements; (c) connection issues, if any, experienced by different mobile RWIS models during transmission of their collected data to the server; and (d) MDSS treatment recommendations compared to plow operator’s treatment applications.

3.2 Conduct interviews with IDOT winter maintenance personnel participating in the pilot study to gather and analyze their experiences installing, utilizing, and maintaining MDSS and mobile RWIS.

3.3 Analyze all collected data from subtasks 3.1 and 3.2 and provide recommendations for improving the performance of mobile RWIS and MDSS in all participating districts in the second winter season of the pilot study (Task 4).

4. Conduct the second phase of the pilot study to evaluate the effectiveness of deployed mobile RWIS and MDSS during the second winter season after implementing the recommendations from task 3.3. The planned research work in this task will be similar to those described in tasks 3.1, 3.2, and 3.3.

5. Analyze the effectiveness of all tested mobile RWIS units and MDSS in improving winter maintenance operations on Illinois roads using widely used performance measures such as level of service, time of clearing, severity index, and cost effectiveness.

6. Identify additional uses for mobile RWIS such as evaluating the effectiveness of different winter maintenance equipment and material such as plow blades, spreaders, pre-treatments, brine, and deicers.

7. Develop recommendations for future deployment of mobile RWIS and MDSS throughout Illinois based on their analyzed performance in the previous tasks as well as their implementation requirements, software/technology needs, operational challenges, and life-cycle costs.

RESEARCH TASKS AND METHODOLOGY

A research team from the University of Illinois plans to accomplish the objectives of this proposed project by adopting a rigorous research methodology. The proposed methodology breaks down the research work into seven major tasks that will lead to five project deliverables, as shown in Figure 18.

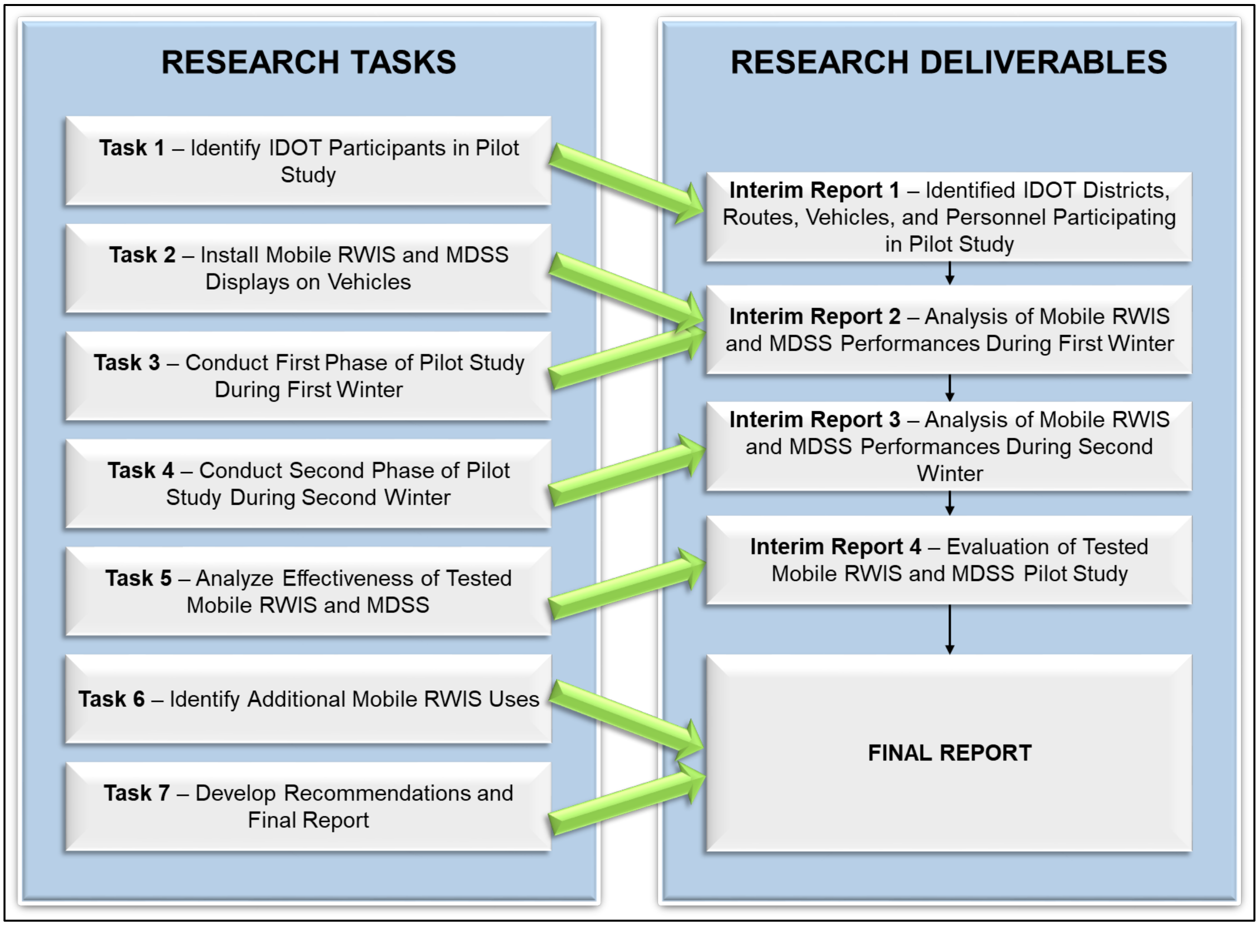


Figure 18. Diagram. Proposed research methodology.

Task 1—Identify Pilot Study Participants

The research team will identify potential districts, personnel, vehicles, and routes that will participate in the pilot study in order to maximize the potential benefits of utilizing mobile RWIS and MDSS units. The planned research work in this task is organized into three main subtasks.

Subtask 1.1—Identify Participating IDOT Districts

The research team in collaboration with the project TRP will identify a list of candidate IDOT districts for the deployment of mobile RWIS and MDSS based on interest from their personnel and the need for such equipment to improve their winter maintenance operations. Preliminary discussions with the TRP of research project ICT R27-SP47 have identified an initial set of candidate IDOT districts including districts 2 (Dixon), 5 (Paris), and 6 (Springfield). This initial set will be further analyzed and updated to identify a final list of preferably three IDOT districts that will benefit the most from participating in the pilot study.

Subtask 1.2—Select Participating Vehicles

The research team will provide recommendations on splitting the mobile RWIS and MDSS units allocated to each participating district between snowplows and supervisor vehicles. The findings of the completed survey of other state DOTs revealed that they recommended installing most of this equipment on snowplows (75%) compared to supervisor vehicles (25%). The main reasons for this recommendation are as follows. Real-time information provided by mobile RWIS can be directly acted upon by snowplows, whereas supervisors would need to contact a snowplow if they identified a roadway that required winter maintenance treatment. Supervisors do not always actively monitor roadways during all storms. The goal of mobile RWIS and MDSS is the effective clearing of roads and material management, which would benefit more from a higher snowplow deployment than supervisor vehicle.

Subtask 1.3—Identify Participating Routes

The research team will analyze the routes within each selected IDOT district to identify candidate routes for the deployment of mobile RWIS and MDSS. The selection of these participating routes in the pilot study will be based on several criteria, including areas with gaps in fixed RWIS coverage, roads with high average daily traffic such as interstate highways, locations with history of blowing snow and/or icy roads, and locations with high rate of winter weather-related crashes.

Task 2—Install Mobile RWIS and MDSS Display on Vehicles

The research team will install mobile RWIS units and MDSS display units on selected plows and supervisor vehicles that were identified in the previous task, which will be implemented in a number of subtasks that will focus on (a) selecting and acquiring 12 mobile RWIS units, MDSS display units, and video cameras for all vehicles that will be equipped with mobile RWIS units; (b) mounting and calibrating mobile RWIS units and MDSS displays on participating vehicles; and (c) providing training to winter maintenance operations personnel on the use of mobile RWIS units and MDSS.

Subtask 2.1—Select and Acquire Mobile RWIS Units

The research team will provide recommendations for the selection and acquisition of new (a) mobile RWIS units and (b) MDSS display units and video cameras that are not currently installed on IDOT vehicles. First, a proposed set of 9 to 12 new mobile RWIS units will be selected and acquired from 3 manufacturers that were utilized and recommended by other state DOTs. Based on the findings of the completed literature review and survey, the three most utilized mobile RWIS units by state DOTs and not currently used by IDOT are Lufft MARWIS, Vaisala MD30, and Teconer. Accordingly, 12 mobile RWIS units are proposed to be acquired from these manufacturers in order to analyze and compare their performance to existing mobile RWIS units on IDOT vehicles, including RoadWatch and PreCise ARC Air & Road Conditions System. Of the three mobile RWIS manufacturers that are not currently used by IDOT, Lufft MARWIS was reported to be the most utilized by 10 different DOTs. Accordingly, an initial alternative acquisition plan for the 12 new mobile RWIS units are 4 Lufft MARWIS, 4 Vaisala MD30, and 4 Teconer. An initial plan for the deployment of these newly acquired mobile RWIS units would provide two types of mobile RWIS model/manufacturer per district per winter season to ensure that each district can objectively compare mobile RWIS models based on their installation, calibration, training, and operation. Note that these initial acquisition and deployment plans of mobile RWIS models will be finalized after consultation with the TRP.

Second, this subtask will investigate and provide recommendations for (a) the integration of MDSS software into existing in-vehicle IDOT displays/spreader controls and/or (b) the acquisition of new

MDSS display units for vehicles operating on the identified routes for MDSS deployment in Task 1. This task will also explore and provide recommendations for the acquisition and installation of video cameras in vehicles equipped with mobile RWIS and/or MDSS units.

Subtask 2.2—Mount and Calibrate Mobile RWIS Units on Vehicles

The research team will coordinate with the mobile RWIS manufacturers/distributors, identified district personnel, and IDOT maintenance personnel to mount and calibrate all newly acquired mobile RWIS units on their assigned vehicles in each district. The findings of the completed survey of other state DOTs revealed that they recommended installing mobile RWIS units on snowplows either directly behind the plow on the front bumper or in the wheelhouse between the vehicle cab and truck bed. Additionally, state DOTs recommended mounting mobile RWIS units on supervisor vehicles on rear of the vehicle, tow hitch, or roof. State DOTs reported minimal issues with these mounting locations on snowplows and supervisor vehicles.

Subtask 2.3—Provide Training to Winter Maintenance Operations Personnel

This task will focus on providing training of the newly installed mobile RWIS and MDSS systems to winter maintenance operations personnel in each identified IDOT district. The research team will coordinate with the mobile RWIS manufacturers/distributors and MDSS developers to ensure that all identified IDOT personnel have sufficient training, manuals, and tools to effectively utilize these devices. To maximize the potential benefits of these training sessions, their timing and list of trainees will be coordinated with each district.

Task 3—Conduct First Phase Pilot Study and Evaluate Results

The research team will conduct the first phase of the pilot study to evaluate the effectiveness of currently utilized and the 12 newly purchased mobile RWIS units and MDSS during the first winter season and to provide recommendations for improving their performance in the second winter season of the project. The planned research work in this task is organized into the following two subtasks: (1) collect and analyze all data generated by mobile RWIS and MDSS during the first winter season and (2) conduct interviews with IDOT winter maintenance personnel participating in the pilot study to gather and analyze their experiences installing, utilizing, and maintaining MDSS and mobile RWIS.

Subtask 3.1—Collect Mobile RWIS and MDSS Data

The research team will collect all data generated by mobile RWIS and MDSS during the first winter season including data on (a) capabilities of different mobile RWIS models in collecting various road and weather data such as road condition, road surface temperature, water film height, ice percentage, friction, ambient air temperature, and relative humidity; (b) performance and reliability of different mobile RWIS units in providing uninterrupted and accurate road and weather data measurements; (c) connection issues, if any, experienced by different mobile RWIS models during transmission of their collected data to the server; and (d) MDSS treatment recommendations compared to plow operator’s treatment applications. The research team will collect the available mobile RWIS and MDSS connectivity data directly from the third party (mobile RWIS and MDSS manufacturer) software database and/or web dashboard. MDSS treatment recommendations will be obtained from the MDSS software database, while plow operator's treatments will be gathered from the in-vehicle spreader controls. In addition to the data collected from mobile RWIS and MDSS, the research team will plan to collect data from fixed RWIS sites on the identified routes in Task 1 to enable a comparison between the road and weather data provided by both mobile RWIS units and fixed RWIS sites.

Subtask 3.2—Conduct Interviews of IDOT Personnel

The research team will conduct interviews with IDOT winter maintenance personnel participating in the pilot study to gather and analyze their experiences installing, utilizing, and maintaining MDSS and mobile RWIS to provide recommendations for improving their performance in the second winter pilot study (Task 4). Interviewed IDOT personnel will be asked to report (1) frequency of utilizing mobile RWIS and MDSS during winter maintenance (e.g., never, once, or twice per winter event, multiple times per winter event/shift, or constantly); (2) overall effectiveness of mobile RWIS and MDSS using a categorical scale that ranges from "very effective" to "not effective"; (3) experienced benefits (e.g., reduced treatment on roadways, improved level of service, decreased time of clearing roads, and lower severity index); (4) problems or challenges encountered as a result of implementing mobile RWIS and MDSS; and (5) recommendations for improving the performance of mobile RWIS and MDSS in the second winter season of the pilot study.

Subtask 3.3—Analyze Collected Data and Provide Recommendations

The research team will analyze all collected data from subtasks 3.1 and 3.2. Based on this analysis, the research team will develop an interim report that provides recommendations for improving the performance of mobile RWIS and MDSS in all participating districts in the second winter season of the pilot study.

Task 4—Conduct Second Phase Pilot Study and Evaluate Results

The research team will conduct the second phase of the pilot study to evaluate the effectiveness of deployed mobile RWIS and MDSS during the second winter season after implementing the recommendations from task 3.3. The planned research work in this task will be similar to those described in tasks 3.1, 3.2, and 3.3. Each participating district will be given an opportunity to rotate its mobile RWIS models before the start of second winter season. For example, if IDOT District 2 utilized two Lufft MARWIS and two Vaisala MD30 during the first winter season, they will be given the opportunity to replace either model with Teconer during the second winter season. This rotation is proposed to enable the collection of more reliable and objective performance evaluation from more than one district for each of the tested mobile RWIS models. These additional evaluations can be used to identify mobile RWIS preferences among IDOT personnel in order to effectively select a mobile RWIS manufacturer for potential statewide implementation.

Task 5—Analyze Effectiveness of Testing Mobile RWIS and MDSS

The research team will analyze the effectiveness of all tested mobile RWIS units and MDSS in improving winter maintenance operations on Illinois roads using widely used performance measures such as level of service, time of clearing, severity index, and cost effectiveness. For example, the research team will analyze the cost effectiveness of mobile RWIS and MDSS units by evaluating all their life cycle costs including initial and operating costs, as well as realized savings such as reduced material usage and manpower cost. The research team will utilize the gathered mobile RWIS and MDSS data in the selected IDOT districts and compare them to historical data on winter maintenance operations in the same districts. The frequency and magnitude of winter events will be normalized to account for variations in annual snowfalls.

Task 6—Identify Additional Mobile RWIS Uses

This task will focus on identifying additional uses for mobile RWIS such as evaluating the effectiveness of different winter maintenance equipment and material such as plow blades, spreaders, pre-treatments, brine, and deicers. Interviews with other state DOT officials have identified the potential of using mobile RWIS to test the effectiveness of alternative winter maintenance equipment and material. Mobile RWIS units have the potential to be incorporated into IDOT/FHWA's Experimental Feature Project process to assist in objectively evaluating materials, processes, methods, equipment items, traffic operational devices, or other features. The research team will investigate additional uses for mobile RWIS units to maximize the benefit of this technology.

Task 7—Develop Recommendations and Final Report

Based on the main findings of the previous tasks, the research team will make final recommendations that can be used by IDOT for future deployment of mobile RWIS and MDSS throughout Illinois based on their analyzed performance in the previous tasks as well as their implementation requirements, software/technology needs, operational challenges, and life-cycle costs. Furthermore, the research team will prepare and submit a final report that documents the entire research effort and the developed recommendations, as shown in Figure 18.

SCHEDULE

The research team plans to complete the project in 36 months, with a planned project start date in August 2022. This proposed schedule enables the research team to collect and evaluate the performance of mobile RWIS and MDSS over two winter seasons to ensure adequate representation and analysis of varying annual snowfalls. Actual dates are subject to modification based on agreement between the research team and the TRP.

HARDWARE AND SOFTWARE BUDGET

The research team has estimated a hardware and software cost of approximately $216,000. This includes mobile RWIS units, MDSS software, and in-vehicle cameras and displays. These proposed hardware and software costs will be finalized based on IDOT recommendations.

REFERENCES

America Association of State Highway and Transportation Officials (AASHTO). 2017. "Integrating Mobile Observations (IMO) and Weather Response Traffic Management (WRTM)." Accessed June 15, 2021. https://systemoperations.transportation.org/wp-content/uploads/sites/22/2017/05/IMO-and-WRTM.pdf.

California Department of Transportation (Caltrans). 2006. *Development and Field-Operational Testing of a Mobile Real-Time Information System for Snow Fighter Supervisors*. Sacramento, CA: California Department of Transportation.

———. 2015. *Mobile Real-Time Information System for Snow Fighter Supervisors—System Design & Test*. Sacramento, CA: California Department of Transportation.

———. 2019. *Mobile Real-Time Information System for Snow Fighter Supervisors—System Design and Test*. Sacramento, CA: California Department of Transportation Division of Research, Innovation and System Information.

Clear Roads (CR). 2021. "Clear Roads Homepage." Accessed November 1, 2021. https://clearroads.org/.

Colorado Department of Transportation (CDOT). 2011. "CDOT Maintenance Crews in the Denver Metro Area Prepare for the Winter." Accessed June 15, 2021. https://www.codot.gov/news/2011news/10-2011/cdot-maintenance-crews-in-the-denver-metro-area-prepare-for-the-winter.

———. 2013. "National Peer Exchange: Snow Operations in Colorado DOT." Accessed June 15, 2021. https://sicop.transportation.org/wp-content/uploads/sites/36/2017/07/2013-SBPR-Colorado_Anderle.pdf.

———. 2015. "CDOT Encourages Denver Metro Motorists to Prepare Vehicles for Winter Driving." Accessed June 15, 2021. https://www.codot.gov/admin/news/2015-news-releases/11-2015-1/cdot-encourages-denver-metro-motorists-to-prepare-vehicles-for-winter-driving.

———. 2021. "Winter Maintenance FAQs." Accessed June 15, 2021. https://www.codot.gov/travel/winter-driving/faqs.html#affects.

Federal Highway Administration (FHWA). 2006. "Maintenance Decision Support System (MDSS)." Accessed March 12, 2021. https://www.fhwa.dot.gov/resourcecenter/teams/operations/ops_mrt1.pdf.

———. 2010. *Maintenance Decision Support Systems: A Proven, Cost-Effective Tool for State and Local DOTs*. Washington, DC: Federal Highway Administration.

———. 2016. *Guidelines for Deploying Connected Vehicle-Enabled Weather Responsive Traffic Management Strategies*. Washington, DC: Federal Highway Administration.

———. 2019. "Integrating Mobile Observations (IMO) Overview." Accessed June 15, 2021. https://ops.fhwa.dot.gov/publications/fhwahop18041/index.htm.

———. 2020a. "Surveillance, Monitoring and Prediction." Accessed September 25, 2020. https://ops.fhwa.dot.gov/weather/mitigating_impacts/surveillance.htm.

———. 2020b. "Weather Responsive Management Strategies (WRMS)—Minnesota DOT Case

Study." Accessed June 15, 2021. https://ops.fhwa.dot.gov/publications/fhwahop19080/index.htm.

———. 2021. "How Do Weather Events Impact Roads?" Accessed June 15, 2021. https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm.

High Sierra Electronics (HSE). 2021. "Mobile Road Weather Sensors for Vehicles." Accessed June 15, 2021. https://hsierra.com/products/mobile-road-weather-devices/.

Indiana Department of Transportation (INDOT). 2007. *Utilizing Wireless Data Network for AVL and Mobile RWIS*. Indianapolis, IN: Indiana Department of Transportation.

———. 2009. *Maintenance Decision Support System (MDSS): Statewide Implementation Final Report for FY09*. Indianapolis, IN: Indiana Department of Transportation.

Intelligent Transportation Systems Digest (ITS). 2017. "The Benefits of Emerging RWIS Technologies." Accessed June 15, 2021. https://www.itsdigest.com/benefits-rwis-road-weather-information-systems.

Lufft. 2021. "MARWIS—Mobile Advanced Road Weather Information Sensor." Accessed June 15, 2021. https://www.lufft.com/products/road-runway-sensors-292/marwis-umb-mobile-advanced-road-weather-information-sensor-2308/.

Massachusetts Department of Transportation (MassDOT). 2016. *Evaluation of Portable Road Weather Information Systems*. Boston, MA: Massachusetts Department of Transportation.

Michigan Department of Transportation (MDOT). 2013. *Road Weather Information System (RWIS) Evaluation: Technology Evaluation Memorandum*. Lansing, MI: Michigan Department of Transportation.

———. 2014. *Weather Responsive Traveler Information System (Wx-TINFO) Implementation: Concept of Operations*. Lansing, MI: Michigan Department of Transportation.

———. 2016. *The Connected Driver: Integrated Mobile Observations 2.0: 2014-2015*. Lansing, MI: Michigan Department of Transportation.

———. 2018a. *Integrated Mobile Observations 3.0 Connected Vehicles for Road Weather Management*. Lansing, MI: Michigan Department of Transportation.

———. 2018b. *Data Use Analysis and Processing II*. Lansing, MI: Michigan Department of Transportation.

Minnesota Department of Transportation (MnDOT). 2013. *Integrated Mobile Observations from Minnesota Department of Transportation*. St. Paul, MN: Minnesota Department of Transportation.

———. 2019. *Mobile Technologies for Assessment of Winter Road Conditions*. Clear Roads Pooled Fund. St. Paul, MN: Minnesota Department of Transportation.

Montana Department of Transportation (MDT). 2017. *Assessment of Montana Road Weather Information System*. Helena, MT: Montana Department of Transportation.

National Center for Atmospheric Research (NCAR). 2021. "Maintenance Decision Support System

(MDSS®).” Accessed March 12, 2021. https://ral.ucar.edu/projects/maintenance-decision-support-system-mdss.

Nevada Department of Transportation (NDOT). 2014. “Maintenance Decision Support System: Pilot Study and Cost-Benefit Analysis.” Carson City, NV: Nevada Department of Transportation.

———. 2016. “Dedicated Short Range Communications (DSRC) Radio for Rural ITS.” Carson City, NV: Nevada Department of Transportation.

———. 2019. *Nevada DOT/USDOT FHWA Road Weather Integrated Mobile Observations (IMO 1, 2 & 3) Projects*. Carson City, NV: Nevada Department of Transportation.

National Operations Center of Excellence (NOCE). 2019. “Road Weather Management Peer Exchange Report.” Accessed June 15, 2021. https://transportationops.org/publications/nocoe-2019-road-weather-management-peer-exchange.

Ohio Department of Transportation (ODOT). 2017*. Effects of Tree Canopy on Rural Highway Pavement Condition, Safety, and Maintenance*. Columbus: Ohio Department of Transportation.

———. 2019. “Project: I-90 Lake County.” Accessed June 15, 2021. https://www.transportation.ohio.gov/wps/portal/gov/odot/programs/tsmo/case-studies/tsmo-case-study-i-90.

———. 2020. *Effects of Tree Canopy on Pavement Condition, Safety and Maintenance—Phase 2*. Columbus, OH: Ohio Department of Transportation.

Parsons Brinckerhoff and Iteris (PB & Iteris, 2013). “Michigan Department of Transportation Road Weather Information System Evaluation: Technology Evaluation Memorandum.”.

Roads and Bridges. 2017. “Mobile RWIS Help Fill in the Gaps.” Accessed June 15, 2021. https://www.roadsbridges.com/everything-between.

———. 2018. “Ohio DOT Combats Winter Weather Using Variable Speed Limits.” Accessed June 15, 2021. https://www.roadsbridges.com/lake-effect.

RoadWatch. 2021. “RoadWatch Sensors.” Accessed June 15, 2021. https://www.roadwatch.com/products.

South Dakota Department of Transportation (SDDOT). 2009. *Analysis of Maintenance Decision Support System (MDSS) Benefits & Costs*. Pierre, SD: South Dakota Department of Transportation.

Teconer. 2021. “Surface Condition and Friction Measurements.” Accessed June 15, 2021. https://www.teconer.fi/en/surface-condition-friction-measurements/.

Transportation Pooled Fund Program (TPFP). 2017. “Development of Maintenance Decision Support System.” Accessed June 15, 2021. https://www.pooledfund.org/Details/Study/240.

United States Department of Transportation (USDOT). 2021. “Crashes during Snow Events Declined 42 Percent after Winter Season Variable Speed Limit Corridor Implementation in Ohio.” Accessed June 15, 2021. https://www.itskrs.its.dot.gov/node/209490.

Vaisala. 2021. “Vaisala Products & Services.” Accessed June 15, 2021. https://www.vaisala.com/en/products.

APPENDIX: INTERVIEW QUESTIONS FOR STATE DOTS

ICT Project R27-SP47: Evaluating the Benefits of Implementing Mobile Road Weather Information Sensors

Interview Questions for DOT Personnel with Mobile RWIS Experience

Background Information of Mobile RWIS and MDSS Use

1. What is your name, title, and bureau/group?
2. How long have you been using mobile RWIS and/or MDSS? What is your role in their deployment?

Mobile RWIS Hardware and Related Implementation

3. Use of mobile RWIS:
    a. What types/models are currently used in your state? (e.g. Lufft, Vaisala, High Sierra, Teconer, others.)
    b. What types/models have you used in the past but are not currently used?
    c. What are the factors/reasons for your current selection?
    d. Did you have any DOT procurement constraints/issues?
4. For each of the following types of vehicles, please list the total number in your fleet and the number of vehicles equipped with mobile RWIS.

	Supervisor (light duty) vehicles	Snowplow (heavy duty) vehicles
Total number of vehicles in fleet		
Number of vehicles equipped with mobile RWIS		

5. For each of the following types of vehicles, please describe the mounting location of mobile RWIS on the vehicles.

	Supervisor (light duty) vehicles	Snowplow (heavy duty) vehicles
Mounting location (e.g. behind plow, mirror, roof, rear, side/wheelhouse, etc.)		
How is it mounted (e.g. bracket type, provide picture if possible)		
Experienced issues with mounting (e.g. dirty/damaged sensor, damaged sensor from vehicle cleaning, inaccurate readings from sensor due to vehicle exhaust, etc.)		
Solutions for mounting issues, if any		

6. What criteria did you use to select travel routes for vehicles with mobile RWIS (e.g. manager selection, busiest routes, highest accidents, problem areas, geographic location, fixed RWIS gap areas, etc.) and what would you consider the top three criteria?

7. What is your current coverage with mobile RWIS/MDSS (e.g. percent of mileage, percent of routes, etc.) and what is your planned expansion in the next 3-5 years?
8. What training was provided for mobile RWIS/MDSS use (e.g. manual, online training, etc.) and who provided it (e.g. manufacturer/vendor, internal, third party, etc.)?
9. How is pre-plowed, and post-plowed data utilized? (e.g. used by plow operator, sent to central DOT for guidance, etc.)
10. Is the collected mobile RWIS data integrated automatically into the road condition reports that are released to the public?

Mobile RWIS and MDSS Software and Communications

11. Does your state utilize MDSS in conjunction with mobile RWIS?
    a. If yes, what MDSS software does your state use? (e.g. custom/agency software, PFS MDSS, Vaisala, etc.)
    b. If yes, how are maintenance recommendations communicated to vehicle operators? (e.g. in-vehicle MDSS display, radio communication, etc.)
    c. If yes, who decides whether to implement the MDSS winter maintenance recommendations? (e.g. state level, district level, maintenance chief level, etc.)
    d. If no, what software does your state use to process and manage mobile RWIS data? (e.g. custom/agency software, Vaisala, Lufft, Declan, etc.)
12. Which of the collected mobile RWIS data do you use to decide winter roadway treatments? (e.g. friction, grip, water film height, road surface temperature, air temperature, etc.)
13. How do your mobile RWIS units communicate with the central DOT server? (e.g. cellular network, dedicated short-range communication, third party communication network, etc.)
14. How is your mobile RWIS data integrated with other systems (AVL, GPS, etc.)? (e.g. single software source, multiple, etc.)

Mobile RWIS and MDSS Costs and Savings

15. For Mobile RWIS and MDSS, please provide the following estimated costs and savings in your department/district.

	Mobile RWIS	MDSS
Operational and maintenance costs (e.g. cellular data, software, maintenance, training, etc.)		
Realized cost savings (e.g. labor, material, annual, etc.)		
Additional benefits (e.g. reduced use of salt/brine, fewer accidents, increased mobility, improved quality of water, wildlife, air, pavement, etc.)		

16. Has your state received any external funding for sensors or software? (e.g. Federal funding, private partnership, etc.)
17. Do you use performance measures to quantify the effectiveness of your state's snow removal operations? (e.g. level of service, time of clearing, severity index, etc.)

Encountered Challenges Utilizing Mobile RWIS and MDSS

18. For Mobile RWIS and MDSS, please list any of the following implementation challenges experienced in your state/department.

	Mobile RWIS	MDSS
Installation challenges (e.g. software integration issues, etc.)		
Operational challenges (e.g. damaged sensors, replacement units, etc.)		
User/personnel challenges (e.g. training issues, buy-in/adoption issues, etc.)		

19. List any additional challenges experienced in operating mobile RWIS units? (e.g. misaligned sensors, inaccurate/non-readings, etc.)
20. Does your state have a documented mobile RWIS deployment plan and lessons learned document/report that you can share?

Required Maintenance for Mobile RWIS

21. How often do you maintain, clean, calibrate your mobile RWIS units? (e.g. before each use, every time in shed, periodically, etc.)
22. Have you experienced any damages in the wiring of mobile RWIS unit from exterior of vehicle to interior? (e.g. cracking due to cold, salt damage, debris damage, etc.)
23. How do you protect mobile RWIS wiring? (e.g. no protection, protective sleeve, permanent wire mount on vehicles, etc.)

Mobile RWIS Data Use, Storage, and Retention

24. Who uses collected data? (e.g. central DOT system, district level, maintenance shed, truck display, other agencies, etc.)
25. Where is the collected mobile RWIS data stored? (e.g. DOT server, cloud server, third party, etc.)
26. How long is collected mobile RWIS data stored? (e.g. annually, seven-year retention, etc.)

Additional Feedback on Mobile RWIS and MDSS

27. Is there any other mobile RWIS information you'd like to share?
28. What recommendations/advice can you provide on implementing a new mobile RWIS/MDSS system?