Mobile Technologies for Assessment of Winter Road Conditions

SRF Consulting Group, Inc.

CLEAR ROADS

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16. Abstract

Mobile RWIS technologies are still relatively new to the market, with only a few early-adopting agencies deploying them, primarily in testing situations. This study provides a comprehensive and comparative analysis of four commercially available mobile RWIS sensors. The sensors in the study include: Lufft's MARWIS, Teconer's RCM411, High Sierra's Mobile IceSight, and Vaisala's DSP310.

Testing was completed in two phases. Phase I focused on the accuracy of different sensor parameters when compared to a known baseline. These tests took place at the MnROAD testing facility, a test track containing a variety of pavement types operated by the Minnesota Department of Transportation. Phase II was conducted in "real-world" settings on active roadways. Sensors measured the environment along a set route in live traffic in a variety of weather conditions.

The study compared the sensors' performance while measuring air temperature, surface temperature, relative humidity, surface condition, water film thickness, and friction. The evaluation also compared qualitative aspects of the sensors such as installation methods. The project found that overall, sensors performed similarly across all parameters. This report ranks sensors by accuracy, but the absolute differences in values used to determine rank are often very small.

The study also developed standardized recommendations for various mobile sensor parameters. While differences across sensors and the high variability in their readings make establishing universal standards difficult, some commonalties were found. The report includes a suggested matrix of a few basic levels categorizing grip, surface state, and mobility impact.

17. Key Words Mobile sensors, Road Weather Information Systems (RWIS), winter maintenance, snowplows, plows, surface condition, friction, winter operations	**18. Distribution Statement** No restriction. This document is available to the public through the Clear Roads pooled fund and the Minnesota Department of Transportation.

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Chapter 1. Executive Summary

1.1. Purpose

Mobile RWIS technologies are still relatively new to the market with only a few early-adopting agencies deploying them, primarily in testing situations. While some studies have tested mobile sensor performance in a laboratory environment or on an individual basis, relatively few tests have been performed on several sensors simultaneously in field conditions.

This study provides a comprehensive and comparative analysis of four commercially available mobile RWIS sensors. The sensors in the study include: Lufft's MARWIS, Teconer's RCM411, High Sierra's Mobile IceSight, and Vaisala's DSP310.

1.2. Test Methodology

1.2.1. Phase I

Testing in Phase I focused on the accuracy of different sensor parameters when compared to a baseline. Testing was conducted at the MnROAD testing facility, a test track made of a variety of pavement types and operated by the Minnesota Department of Transportation. Measurements were taken simultaneously from each sensor as well as a baseline, then compared for accuracy. Parameters measured included air temperature, surface temperature, relative humidity, surface conditions, and water film thickness. Friction, as a unitless value, did not have a baseline measurement for comparison and was not included in Phase I evaluations.

1.2.2. Phase II

Phase II was conducted in "real-world" settings. Sensors measured the environment along a set route in live traffic in a variety of weather conditions. Sensors were mounted on a trailer and angled so that all sensors were scanning approximately the same region of the trailer's wheel path. Testing in Phase II replicated conditions similar to what may be experienced if sensors were attached to a plow. Sensor data were compared against each other since a baseline data source was not available.

1.3. Project Findings

1.3.1. Phase I and II

Air Temperature

Sensors performed similarly in both phases. Compared to the baseline, the average percent error fell between 5.8% and 14.6% (Table 3). The Lufft MARWIS had the lowest average percent error when compared to the baseline. All sensors required an acclimation period if outdoor temperatures were lower than the garage temperatures, though all adjusted within 10 minutes.

Surface Temperature

In baseline testing, all sensors had an average percent error of less than 10%. The Lufft MARWIS had the lowest average percent error overall across all pavement types. However, the Vaisala had a lower average percent error on aggregate and asphalt surfaces (Table 4). Surface temperature also required an acclimation time when transitioning from indoor to outdoor temperatures, though it was shorter than the air temperature acclimation time. Consistently, the High Sierra and Lufft sensors reported surface temperatures 2-3^{o}F above the Teconer and Vaisala.

Relative Humidity

The High Sierra, Vaisala, and Lufft devices measure relative humidity. As with surface and air temperature, the sensors performed comparably, but the Lufft sensor had the lowest average percent error (Table 5). The Lufft sensor appeared to react faster to changes in humidity, increasing its accuracy.

Surface Condition

Unlike the other sensor parameters measured in this report, surface condition is not a numerical value. Additionally, each sensor reports different surface states with different definitions (Table 12). Accuracy of surface condition reporting was determined by comparing readings with visual observations. The Vaisala device had the greatest accuracy by this measure, though all devices performed similarly (Table 6).

Water Film Thickness

Only three sensors measure water film thickness: Teconer, Vaisala, and Lufft. This parameter had a large amount of variability between sensors, though there was still correlation with changes in magnitude and direction for a given time interval. Baseline measurements were conducted using a wet film comb on a smooth Plexiglas surface, as rough or aggregate surfaces could not establish a reliable baseline. Vaisala had the lowest average percent error during tests. Teconer and Lufft had high errors when water film height was low but improved as water height increased (Table 8).

Friction

Friction is represented by a scalar number referred to as a “coefficient of friction” which differs depending on many properties, making it difficult to measure against a baseline value. As a result, Phase I did not include friction analysis, and readings were only compared against each other.

Sensors report friction in a range between 0 and 1. The values at any given moment were often vastly different between sensors, though sensors appeared to correlate to one another in detecting changes in friction (Figure 41).

While all sensors correctly detected changes in friction, the interpretation of the values differs between each manufacturer. It is therefore recommended that sensor manufacturers establish a clear definition for different ranges of friction. An example of this is included in Table 16, where friction is shown with relation to surface state and surface condition.

1.3.2. Standards

Differences across sensors and the high variability in their readings make establishing universal standards difficult. Using the test results from Phase I and II, past research, and input from Clear Roads members, this project developed a set of standardized recommendations. Table 18 categorizes grip, surface state, and mobility impact into a set of simple levels. This categorization allows for a more practical application of friction values.

1.4. Recommendations

In summary, sensors performed similarly across all parameters. Table 19 provides rankings of performance based on the accuracy calculated in Phase I. While the devices are ranked, the differences in values used to rank the parameters are often very small. Adjustments to the mounting height or location may greatly change sensor data. Thus, it is recommended that agencies select sensors based on the factors they value most, including both parameter accuracy and factors such as cost and installation.

Additionally, the accuracy of sensors did not meet the accuracy desired from Clear Roads members that were surveyed (Figure 7). As such, Clear Roads members request that manufacturers continue working to improve accuracy, especially in field applications.

Chapter 2. Acknowledgements

The project committee and research team would like to acknowledge and thank Vaisala, High Sierra Electronics, Teconer, and Lufft for their contributions in this evaluation.

All vendors provided exceptional service and provided the research team with one of their mobile sensors for the duration of the project. The project team and the Clear Roads research consortium greatly appreciate the partnerships and relationships which facilitate these types of projects and look forward to additional opportunities to partner in future endeavors.

Chapter 3. Introduction

Clear Roads is a research organization comprised of 36 agencies that pool resources to conduct research on winter maintenance operations. Since its inception in 2004, the Clear Roads research program has supported dozens of research projects focused on the improvement and facilitation of winter weather maintenance operations. For the past several years, Clear Roads has focused research on the implementation of new field technologies and on data collection. This research has identified the need for a better understanding of the capabilities and limitations of newly developed mobile Road Weather Information Systems (RWIS) when utilized as part of a winter event response.

Clear Roads initiated CR 16-03 to gain insight on mobile sensor performance and to aid in the development of data and technological standards. This project included preparation of a literature search and evaluation test plan, followed by field studies to assess the performance of various commercially-available mobile RWIS sensors. This Final Report summarizes the project's deliverables and key findings.

Chapter 4. Background

4.1. Road Weather Information Systems (RWIS)

RWIS frequently refers to strategically placed sensor stations that automatically gather real-time weather information on atmospheric and pavement surface conditions. The data reported by RWIS stations is often an integral part of winter maintenance operations and planning, as it allows agencies to make informed decisions about plowing/chemical application and communicating road conditions to the public.

Current RWIS technology is limited to reporting conditions near the stations, often requiring extensive, costly networks to be deployed, or leaving wide gaps in data across a region. As an alternative solution, many RWIS vendors have developed mobile, vehicle-mounted weather sensors to help supplement stationary RWIS locations and fill in data gaps to more accurately reflect road conditions. The data collected by mobile RWIS sensors allows agencies to make decisions for specific roadways with higher precision and accuracy than traditional RWIS data.

4.2. Project Goals

The goals outlined for this project were developed based on the capabilities of each sensor and results from a survey of Clear Roads members. Tests were designed to address the identified goals and objectives and determine best practices and guidelines for each of the sensors. The goals of the project were:

4.2.1. Goal 1: Determine the accuracy for each parameter of the test sensors

- Test sensor accuracy in a controlled roadway environment for the following parameters (as applicable for each sensor):
    - Air temperature
    - Relative humidity/Dew point
    - Surface temperature
    - Water film height
    - Friction coefficient (grip)
- Test accuracy in determination of pavement status using qualitative and quantitative measures (varies based on sensor output—examples include: dry, moist, wet, chemical wet, ice, snow, slush, frost).

4.2.2. Goal 2: Assess practical aspects of using the sensors.

- Identify suitable locations for mounting each sensor and document the sensor mounting process. Also, work to determine the effects of mounting height on sensor performance and accuracy.

- Qualitatively describe sensor software and document how it can be integrated with other data management and physical systems.
- Document specifics about sensor data outputs and terminology to be used to develop recommendations for standardized language to describe pavement conditions.
- Assess sensor performance and variability under real-world, live traffic conditions.

Literature Search

The literature review completed as part of this investigation documents the state of practice regarding mobile pavement condition sensors. Sources for this document include a review of papers submitted to the Transportation Research Board, a web review of data sources, and direct contacts with several sensor vendors. A secondary literature search was conducted to develop standards and recommendations for the long-term improvement of mobile RWIS sensors as they integrate more regularly into agency operations. Those results are documented in the 'Standards Development and Recommendations' section of this report.

4.2.3. Laboratory Tests

While previous studies have tested mobile sensor accuracy on an individual sensor basis, relatively few studies have tested many sensors simultaneously. One such test was done by Wåhlin[1] who tested five different sensors under controlled laboratory conditions. In general, sensors correctly identified pavement surface states, but there was inconsistency when identifying wet and ice conditions on dark pavement.

None of the tested sensors were found to distinguish between different types of snow. The report indicated that "hard packed icy snow reported the same as soft loose snow." However, the friction estimates were more closely correlated between sensors. Studies note that even small friction differences result in much different driving conditions, so it is important to be very accurate when estimating friction relative to other parameters.

Figure 1 shows a results summary table of some of the laboratory test results.

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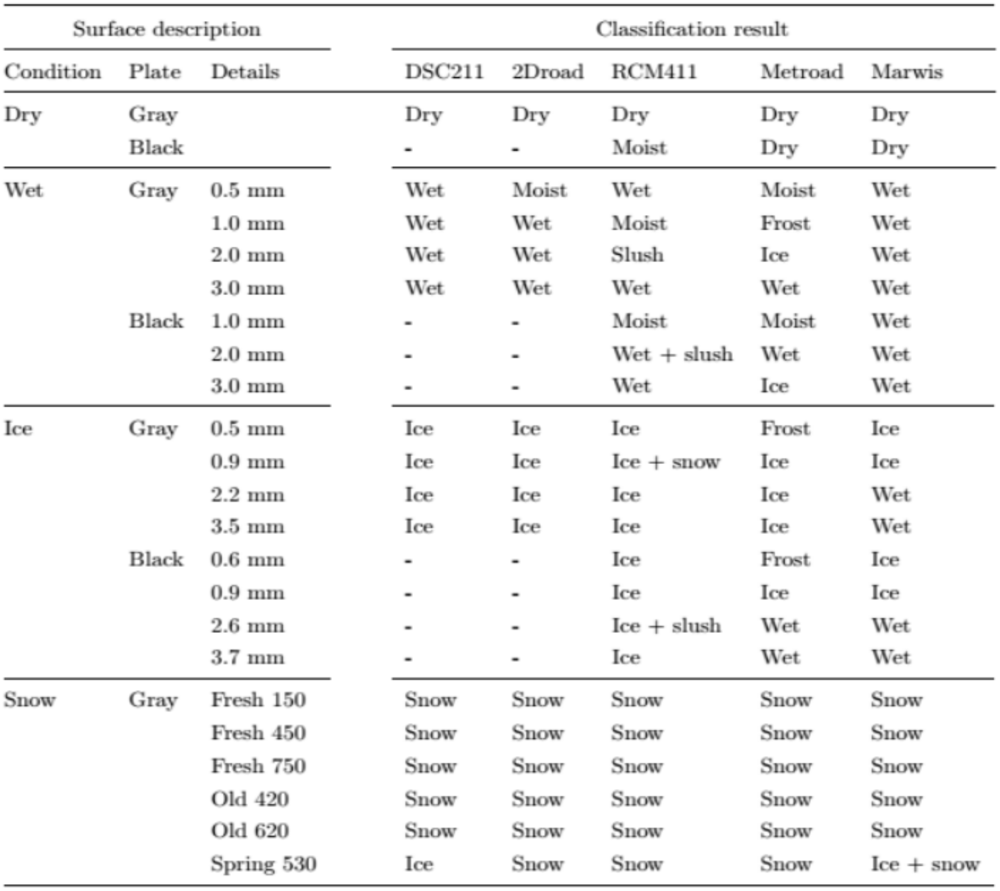
[1] Wåhlin, J. Laboratory test of five different optical road condition sensors. Norwegian University of Science and Technology.

Figure 1. Results of Wåhlin, J., Laboratory test of five different optical road condition sensors.[2]



Surface description			Classification result				
Condition	Plate	Details	DSC211	2Droad	RCM411	Metroad	Marwis
Dry	Gray		Dry	Dry	Dry	Dry	Dry
	Black		-	-	Moist	Dry	Dry
Wet	Gray	0.5 mm	Wet	Moist	Wet	Moist	Wet
		1.0 mm	Wet	Wet	Moist	Frost	Wet
		2.0 mm	Wet	Wet	Slush	Ice	Wet
		3.0 mm	Wet	Wet	Wet	Wet	Wet
	Black	1.0 mm	-	-	Moist	Moist	Wet
		2.0 mm	-	-	Wet + slush	Wet	Wet
		3.0 mm	-	-	Wet	Ice	Wet
Ice	Gray	0.5 mm	Ice	Ice	Ice	Frost	Ice
		0.9 mm	Ice	Ice	Ice + snow	Ice	Ice
		2.2 mm	Ice	Ice	Ice	Ice	Wet
		3.5 mm	Ice	Ice	Ice	Ice	Wet
	Black	0.6 mm	-	-	Ice	Frost	Ice
		0.9 mm	-	-	Ice	Ice	Ice
		2.6 mm	-	-	Ice + slush	Wet	Wet
		3.7 mm	-	-	Ice	Wet	Wet
Snow	Gray	Fresh 150	Snow	Snow	Snow	Snow	Snow
		Fresh 450	Snow	Snow	Snow	Snow	Snow
		Fresh 750	Snow	Snow	Snow	Snow	Snow
		Old 420	Snow	Snow	Snow	Snow	Snow
		Old 620	Snow	Snow	Snow	Snow	Snow
		Spring 530	Ice	Snow	Snow	Snow	Ice + snow

A 2005 laboratory study conducted by the Aurora Consortium[3] tested fixed and mobile sensors in a controlled environmental chamber to regulate temperature and snow conditions. This study found that accuracy for fixed, non-intrusive sensors was generally comparable and relatively accurate when compared against sensors that make direct contact with pavement. The two mobile sensors evaluated had generally comparable results to the fixed sensors, although the accuracy was more variable. Solar heating (solar impact) on the test area caused the greatest discrepancies between

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[2] Wåhlin, J. Laboratory test of five different optical road condition sensors. Norwegian University of Science and Technology.

[3] SRF, The Aurora Consortium: Laboratory and Field Studies of Pavement Temperature Sensors. 2005

results, emphasizing the need to control as many environmental variables as possible when conducting field tests. Table 1 shows complete results from the study:

Table 1. Results from Aurora Study: Laboratory Studies of Pavement Temperature Sensors.[4]

Test Description:	Fixed Temperature 5° C		Fixed Temperature 0° C		Fixed Temperature -6° C		Fixed Temperature -17° C		Declining Temperature		Increasing Temperature	
TEST NO.	1-1a		1-1b		1-1c		1-1d		1-2a		1-2b	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.16	0.24	0.03	0.12	1.06	1.23	0.11	0.06	1.74	4.75	1.52	2.91
BOSCHUNG	1.82	0.19	0.20	0.16	0.22	0.19	0.06	0.06	1.22	0.26	1.10	0.36
LUFFT	0.21	0.08	0.11	0.03	0.10	0.05	0.53	0.40	0.36	0.42	0.55	0.35
POINT 6	1.60	0.89	0.38	0.74	0.20	0.07	0.23	0.27	0.54	0.29	1.43	1.17
SSI	0.45	0.49	0.40	0.30	0.73	0.58	0.74	0.60	1.23	0.97	0.14	0.15
VAISALA	0.13	0.12	0.08	0.11	0.07	0.12	0.08	0.05	0.13	0.19	1.16	0.14
SPRAGUE	0.78	0.52	1.13	0.36	1.53	0.46	1.56	0.33	N/A	0.98	N/A	0.68
CONTROL PRODUCTS	0.20	0.20	0.08	0.10	0.55	0.30	1.20	0.31	N/A	0.75	N/A	0.70

Test Description:	Cold Pavement w/o Solar Impact		Cold Pavement w/ Solar Impact		Warm Pavement w/ Snowfall		Cold Pavement w/ Rainfall		Iced Pavement w/ Rainfall		Compacted Snow (melting)	
TEST NO.	1-5a		1-5b		1-6		1-7		1-8		1-9	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.31	0.31	3.35	3.17	1.34	1.05	0.85	0.62	0.43	0.58	1.20	0.56
BOSCHUNG	0.17	0.16	0.97	0.55	0.85	0.32	0.65	0.63	0.44	0.34	0.88	0.56
LUFFT	0.16	0.06	0.23	0.16	0.46	0.15	0.90	0.92	0.31	0.30	0.55	0.60
POINT 6	0.28	0.19	0.68	1.47	0.76	0.67	1.27	0.74	0.97	0.77	0.61	1.12
SSI	0.50	0.54	2.10	1.52	0.55	0.47	1.42	1.17	0.67	1.09	0.39	0.76
VAISALA	0.07	0.08	3.35	1.23	0.79	0.76	1.17	0.75	0.89	0.62	N/A	N/A
SPRAGUE	1.13	0.47	1.15	N/A	1.01	0.37	1.96	N/A	1.98	0.83	1.39	0.63
CONTROL PRODUCTS	0.10	0.15	2.80	0.63	0.56	0.71	0.95	0.49	0.67	0.42	1.76	0.87

Test Description:	Frost Depositing		NaCl: Cold w/o Solar Impact		NaCl: Cold w/ Solar Impact		NaCl: Warm w/ Snow		NaCl: Cold w/ Rainfall		NaCl: Iced Pavement w/ Rainfall	
TEST NO.	1-10		2-1a		2-1b		2-2		2-3		2-4	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
AANDERAA	0.66	0.62	0.09	0.05	2.14	1.68	1.58	1.06	0.50	0.51	0.67	0.52
BOSCHUNG	0.52	0.22	0.22	0.18	0.51	0.46	0.28	0.63	0.37	0.26	0.45	0.26
LUFFT	0.37	0.24	0.10	0.10	0.31	0.37	1.10	0.28	0.60	0.59	N/A	N/A
POINT 6	1.27	N/A	0.18	0.14	1.76	1.17	0.72	0.57	1.08	0.56	1.34	0.74
SSI	0.38	0.32	0.62	0.43	2.62	1.44	0.44	0.51	0.68	0.77	1.10	0.97
VAISALA	0.20	0.14	N/A	N/A	2.15	1.16	0.71	0.60	0.34	0.48	0.38	0.54
SPRAGUE	1.21	N/A	0.82	N/A	0.71	N/A	0.94	N/A	1.27	N/A	2.02	N/A
CONTROL PRODUCTS	0.80	0.51	0.30	0.16	2.61	0.20	0.93	1.06	0.54	0.39	0.39	0.38

4.2.4. Field Tests

In general, field tests have focused on testing one or two sensors at a time. One such test was done by Kiuru et al.[5] and tested the Teconer RCM-411. This study assessed the performance and accuracy of the friction instrument used in the mobile road weather sensor. Results from the study reported that the RCM-411 models friction based on optical snow and ice detection. Plots of the results show that the sensor roughly correlated with the baseline, but there was a significant amount of scatter and there were several outlier points at approximately 0.8 friction with the baseline ranging from 0.3 to 0.6. The scatter plots are shown in Figure 2.

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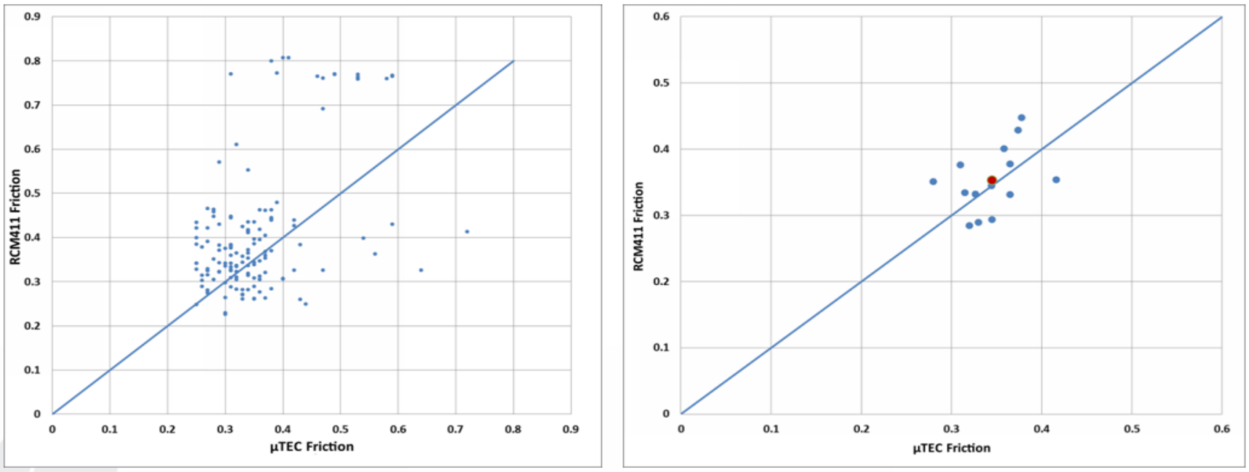
[4] SRF, The Aurora Consortium: Laboratory and Field Studies of Pavement Temperature Sensors. 2005

[5] T. Kiuru, J. Valtonen & T. Pellinen, Department of Civil and Environmental Engineering, Aalto University, Finland

Figure 2. Results from Kiuru et al, Friction compared to µ Tec baseline.[6]



All braking measurements.

- Std. Dev. of difference about 0.10

Average of single point measurements.

- Std. Deviation of difference 0.046

In a 2011 study, Malmivu[7] simultaneously collected data from the Teconer RCM-411 and Vaisala's DSP-310 along with three other baseline sensors. The two subject sensors are plotted as a time series with the baseline sensors reported as points. This graph shows that there was a relatively good correlation between the DSP-310 and RCM-411 sensors, although the DSP-310 appears to provide much less consistent readings.

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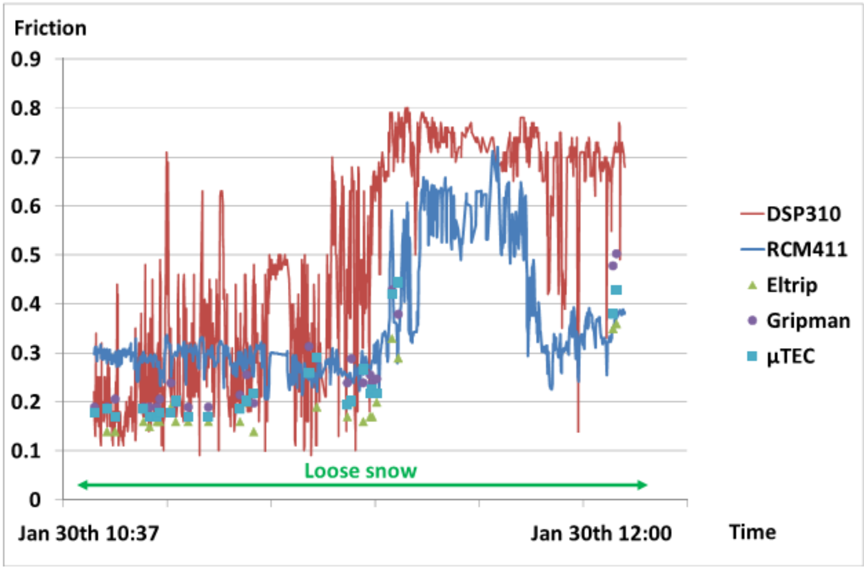
[6] T. Kiuru, J. Valtonen & T. Pellinen, Department of Civil and Environmental Engineering, Aalto University, Finland

[7] Malmivu, M. Friction Meter Comparison Study, 2011.

Figure 3. Results from Malmivu, M. Friction Meter Comparison Study, 2011.



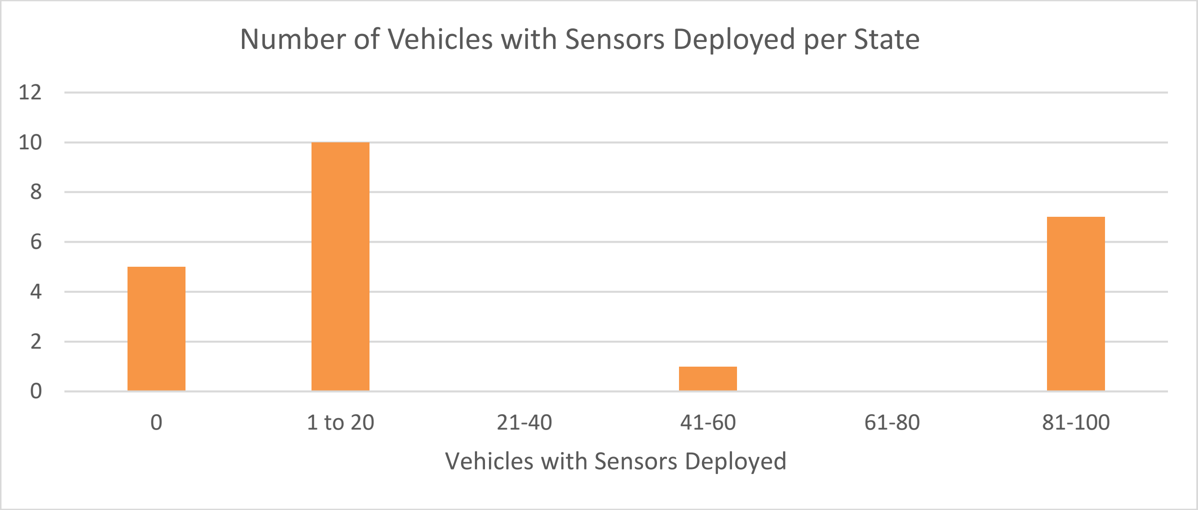
4.3. Current Practices and Desired Outcomes - Member Survey

Before testing began, a survey of Clear Roads members was conducted. The survey's goal was to understand current mobile sensor use and to help define the scope of the project. Survey questions focused both on existing practices for road weather data collection practices and on desired uses or performance levels of the mobile units being tested. The survey response rate was very good with 31 responses representing 28 agencies.

Respondents were asked about the number of sensors their agency currently has deployed and the number they plan to deploy in the next three years. While the number of sensors varied greatly between agencies, 78% reported having at least one sensor, and 30% reported having over 80 sensors. A graph of all the responses is shown in Figure 4.

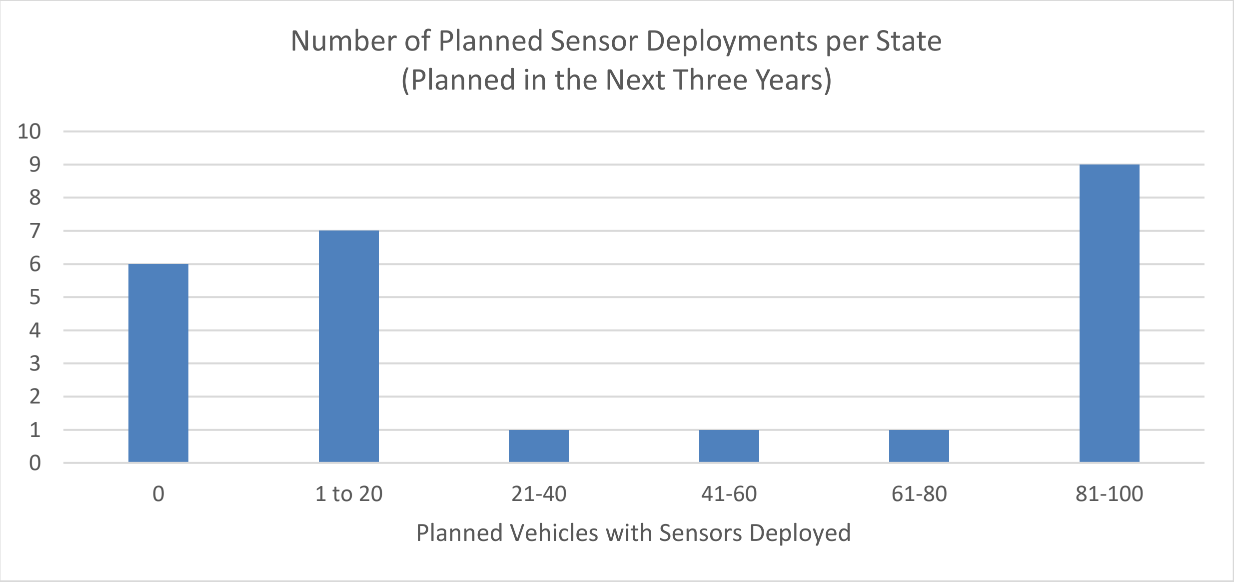
When asked which, if any, sensors were currently being used by agencies, seven states responded that they were using the Lufft sensor, four were using the Vaisala, three were using the Teconer, and three were using the High Sierra. Nine states reported that they used no sensor.

Figure 4. Number of Vehicles with Sensors Deployed per State



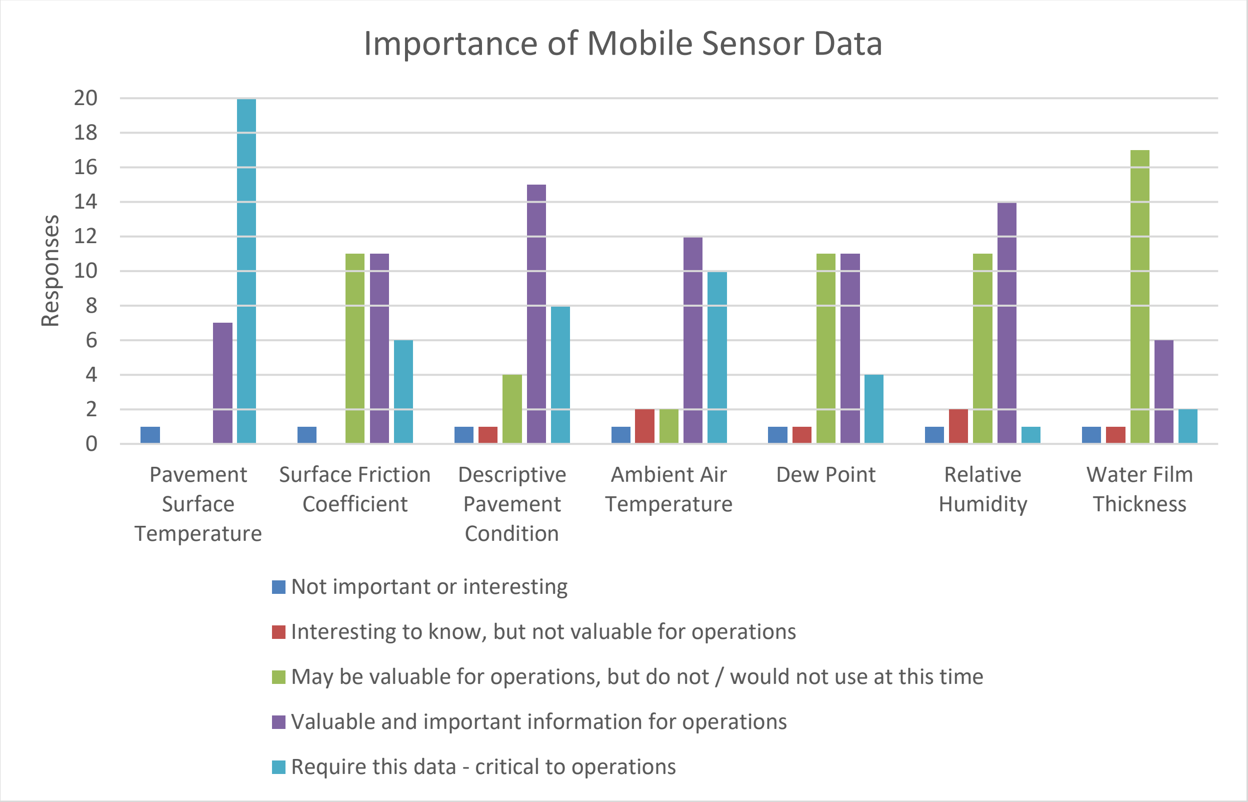
Additionally, respondents were asked about the number of vehicles they planned to have sensors deployed to in the next three years. Again, survey responses differed widely, but 76% planned to have at least one sensor and 36% planned on deploying over 80 sensors. The survey results are included in Figure 5. The high number of agencies currently using or intending to use sensors reiterated the value of researching sensors to allow agencies to make informed purchasing decisions.

Figure 5. Number of Planned Sensor Deployments per State



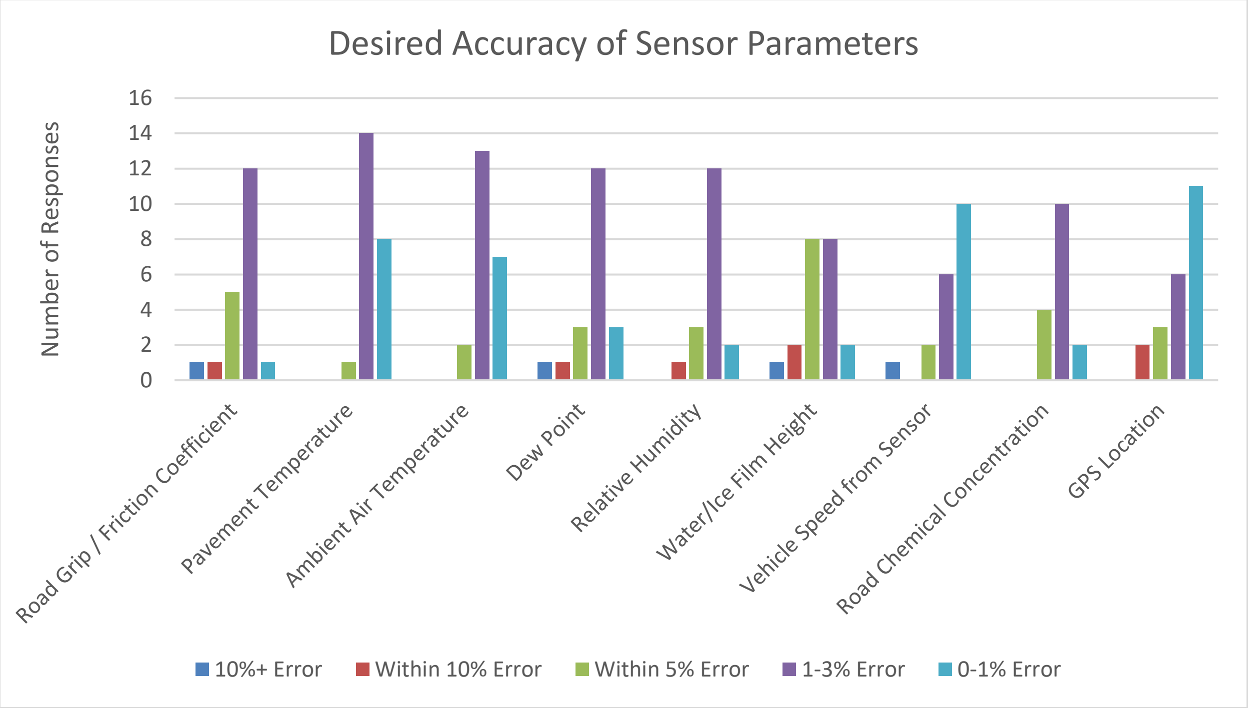
Agencies were also asked about the utility of various reported data parameters for winter maintenance operations. The reported importance of each data parameter is shown below in Figure 6.

Figure 6. Importance of Mobile Sensor Data



Additionally, survey respondents were asked what their desired percent accuracy was for different parameters. Overall, the majority of respondents desired an accuracy of 1-3% error for each factor. The responses are below in Figure 7.

Figure 7. Desired Accuracy of Sensor Parameters



In addition to the types of data, the physical installation of the sensors was of interest to survey respondents. Mounting locations and methods vary between agencies and has a major impact on results. Surface conditions will be different between the center of the road in front of the plow versus the wheel path after a plow has passed. When asked about current or planned sensor mounting locations, the trailer hitch and side mirrors were the most common responses. Most agencies also reported the wheel path as the desired focus of the sensors. This influenced the design of the testing vehicle, where the sensors were mounted onto a trailer and aimed along the wheel path.

Sensor data is collected for a variety of uses. Most commonly, 78% of respondents reported they used the data for material application. Other prominent uses of sensor data included plow timing and plowing frequency which were reported as 57% and 43%, respectively.

Chapter 5. Sensors for Evaluation

5.1. Lufft MARWIS

Lufft's MARWIS was released in November of 2014 with a second version released in April of 2016. Version 2.0 added the capability to collect ambient air temperature and humidity information. Other measurements taken by the MARWIS include: pavement temperature, dew point, water/ice film height, six reportable surface state conditions, and a surface friction coefficient. The six reportable surface state conditions for the MARWIS include: dry, moist, wet, ice, snow/ice, and critically/chemically wet. The critically/chemically wet condition occurs when wet conditions are detected with surface temperatures reported below the freeze point (indicating the presence of chemicals or the near possibility of ice forming).

As the MARWIS is Bluetooth enabled, the only limitation on mounting location would be the distance of a standard Bluetooth data transmission (~30 feet) and where the user is interested in collecting data. The recommended mounting height above the detected surface is 1-2 meters. If connecting to a modem or AVL system, a 15-foot cable is provided, but customizable lengths of the standard cable can be requested, as necessary. The vendor noted that sensors have been placed on the front of a vehicle or on the rear between the tires. They also noted that Michigan DOT has mounted several of these sensors on plows.

Several agencies are currently using or testing Lufft's MARWIS, including: the Arkansas Highway Department, Minnesota DOT, Missouri DOT, Indiana DOT, North Dakota DOT, Nevada DOT, Ohio DOT, New York City DOT, Colorado DOT, Michelin Tire Company (for tire testing), and several school districts on the east coast. The anticipated useful life of each sensor is unknown due to the nature of a newer product, but Lufft has had several sensors in the field for over four years at the time of this report and all are still operational. MARWIS sensors are available direct from Lufft or from any of their four channel partners, which cover over 30 states.

Figure 8. Lufft MARWIS

5.1.1. Specifications

The MARWIS device operates from 12-28 VDC. In temperatures below 14ºF, the vendor recommends the power supply be increased to 24V to ensure the heating performance in the sensor is adequate. The power input is 3 VA without heating, and 50 VA with heating.

The operating temperature is -40 to 140ºF and operating relative humidity is from 0 to 100%.

5.1.2. Connecting to Sensors

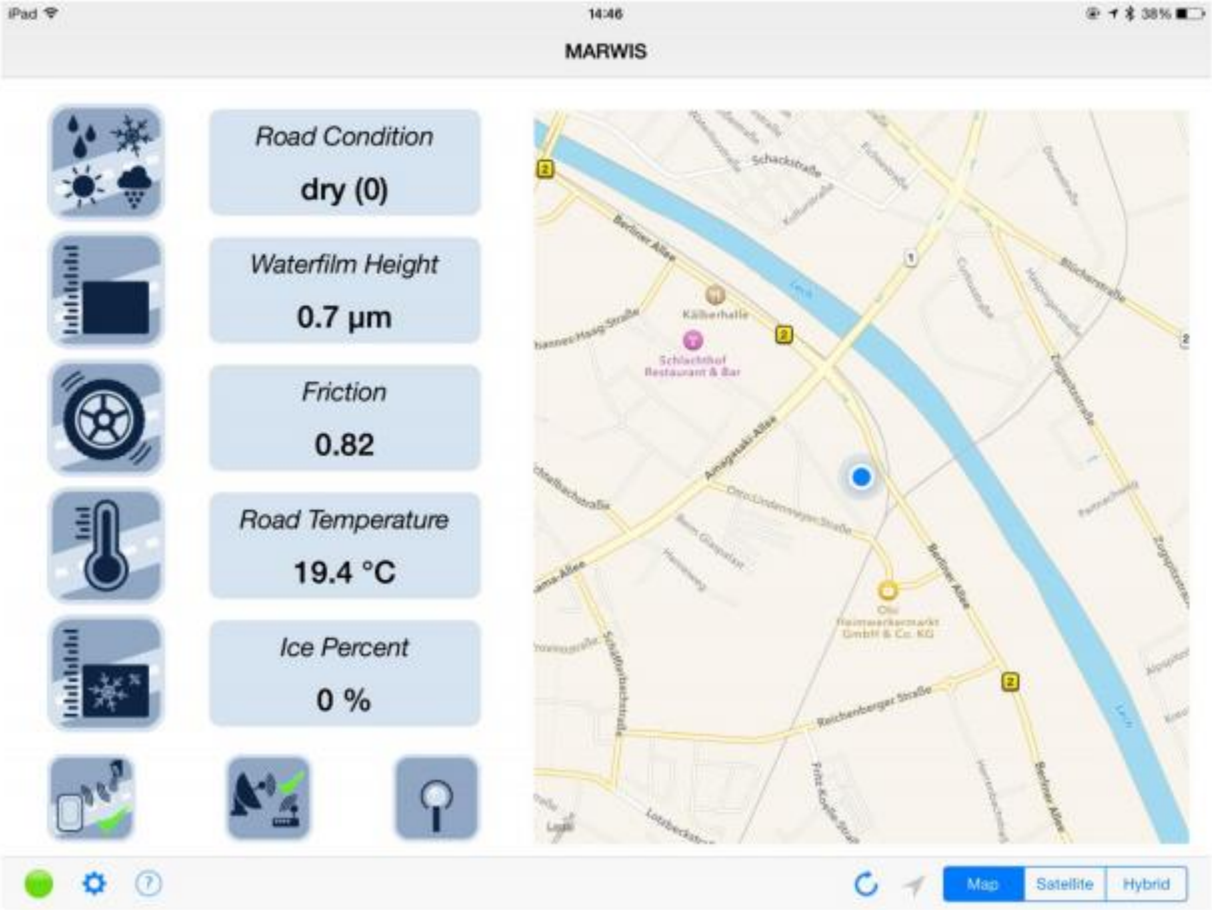
MARWIS data is sent via RS485 or Bluetooth to an iOS/Android device or to a modem/AVL device. The sampling rates for parameters can be adjusted to sample between once per 0.1 seconds and once per 5 seconds using the RS485 connection. Data can be imported into a Maintenance Decision Support System (MDSS) across a variety of different platforms with GPS location and vehicle speed being pulled from the iOS or Android device.

MARWIS has been integrated into several different software packages and can send data via CSV or VMONDO which is Lufft's proprietary system. Regular firmware updates are pushed every 2-3 months and occur automatically through the sensor's software.

5.1.3. Mobile Interface

Lufft's mobile interface is simple and easy to use. Its main screen displays a map of the route alongside the current sensor readouts of road condition, water film height, friction, road temperature, and ice percent. The units of each metric can be changed within the app. Status icons display the Bluetooth and server connection next to an indicator of GPS signal quality. The map displays the route travelled during the run, and the map background can be changed quickly. A screenshot of the main page of the mobile application is shown in Figure 9.

Figure 9. Lufft MARWIS Mobile Application



Road Condition
dry (0)

Waterfilm Height
0.7 µm

Friction
0.82

Road Temperature
19.4 °C

Ice Percent
0 %

5.1.4. Calibration

Calibration is simple and takes approximately 45-60 seconds. While calibrating, the Lufft MARWIS should be positioned over dry road in a stationary position. The temperature should be less than 86° F and calibration should not be conducted under artificial light. Calibration can be initiated from the MARWIS app on a connected phone or tablet. Instructions and options for calibration are included in the manual. The MARWIS also offers customizable presets for calibration if the sensor is moved between vehicles or to various locations on a single vehicle.

5.1.5. Cleaning and Maintenance

The Lufft MARWIS should be checked periodically to ensure the lens is clear and reading conditions correctly. If the sensor is dirty, use a gentle, damp cloth with mild detergent to clean the lens. Check mounting, cables, screws, etc. regularly for looseness or damage.

5.1.6. Manual

The Lufft MARWIS manual is 56 pages long and includes equipment information, output and measurement information, mounting, connection and setup, and technical information. The manual contained sufficient information to install, calibrate and use the sensor without additional support from the manufacturer. The manual can be found here.

5.1.7. Size

The Lufft MARWIS can be mounted with a long or short protective covering. For this study, the short protective covering was used. The device dimensions compared to an average-sized human hand are shown in Figure 10.

Figure 10. Lufft MARWIS Dimensions

Average Human Hand

Lufft MARWIS with Short Protective Covering Front

Lufft MARWIS with Long Protective Covering Side

5.2. Teconer RCM411

Teconer's RCM411 measures pavement temperature, ambient air temperature, dew point and humidity (optional), water film height, six surface state conditions, and a friction coefficient. The six reportable surface state conditions include: dry, moist, wet, slush/ice/snow with water, ice, and snow. The mobile application tracks vehicle speed and GPS location and adds it to the recorded data.

The RCM411 is notable in that it is designed for use with passenger vehicles by connecting to a 50-mm ball joint towing hitch receiver. An adapter is also available to install the sensor to the rear door or bumper of a vehicle. The optimal location for installation is the front of a vehicle just behind the front grill – though space is usually limited here which is why the sensor was designed for mounting to a trailer hitch. The standard mount is set up to monitor the left tire track but can be adjusted to monitor the right tire track. The maximum mounting height is two meters, though the recommended height is approximately 20-22 inches. Cables and connectors are supplied for immediate use with the standard cable length being three meters.

Teconer estimates the useful life of each RCM411 to be approximately 10 years, though some mechanical parts, such as bolts or safety pins, may need replacement before then. The RCM411 is being used by several DOTs and globally by national and local road and airport agencies.

Figure 11. Teconer RCM411

5.2.1. Specifications

The Teconer RCM411 operates with a power supply of 9 to 30 VDC, which can be powered from a trailer light connector or cigarette lighter in the vehicle. Its power consumption is approximately 1 watt. The operating temperature for the RCM411 is -22 to 122°F.

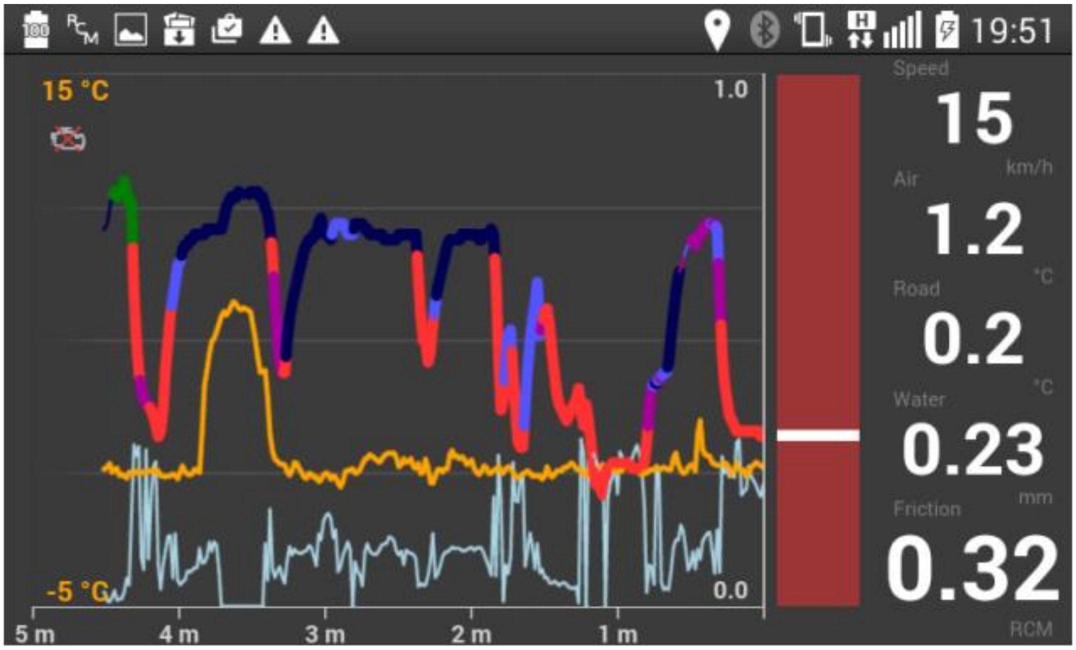
5.2.2. Connecting to Sensors

Data is transmitted once every second to a Bluetooth unit which is connected to an Android cell phone containing a user interface application. The Android software then transfers data every 15 seconds to a server where data can be readily accessed for MDSS programs. The Bluetooth settings cannot be changed without special equipment and must be configured by the supplier or manufacturer.

5.2.3. Mobile Interface

The Teconer RCM411 mobile interface is similar to the Lufft MARWIS. It displays key parameters on one side of the screen, giving the current sensor reading for speed, air temperature, road temperature, water film height, and friction. On the other side of the screen, instead of a map, there is a line graph with three separate lines. The thicker line represents friction, and changes color based on the road surface state. The thinner two lines represent surface and air temperature. This graph displays previous data from the run instead of just instantaneous readings. It was noted that the additional information may make it harder to read and comprehend the graph quickly. The display be customized to remove values the user does not wish to see. Figure 12 contains an example screenshot from the mobile application.

Figure 12. Teconer RCM411 Application User Interface



5.2.4. Calibration

The Teconer RCM411 is factory calibrated for dry road surfaces from 50-55 cm from the sensor. If the sensor appears to need recalibration and the lens is clean, recalibration can be initiated from the app using the calibrator, a piece of plastic equipment that comes with the device. If recalibration due to mounting at a height or angle outside of recommendations is required, it can be done in about two minutes.

5.2.5. Cleaning and Maintenance

The Teconer RCM411 should be checked periodically to ensure the lens is clear and reading conditions correctly. If the sensor is dirty, use a gentle, damp cloth with mild detergent to clean the lens. Though not written expressly in the manual, periodic checks of mounting, cables, screws, etc. are recommended.

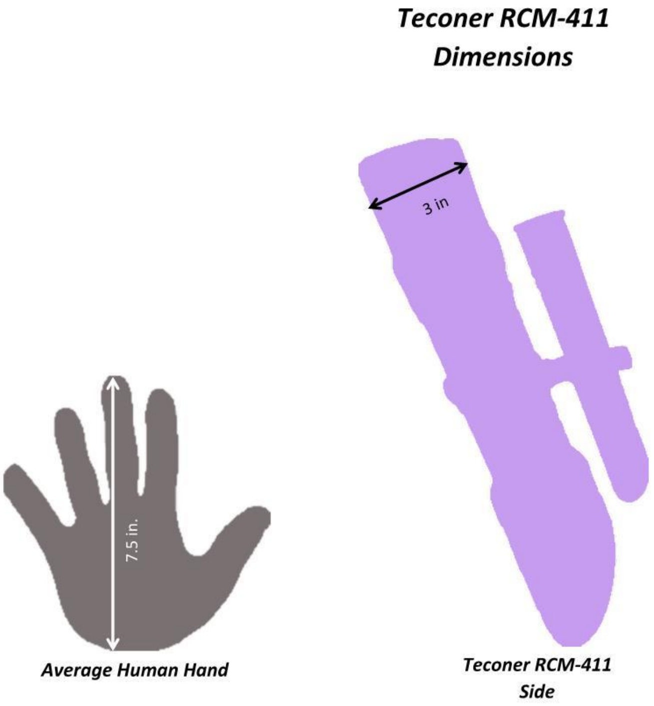
5.2.6. Manual

The Teconer RCM411 manual is 22 pages long and contains installation instructions, mobile application settings and instructions, calibration, operation, and troubleshooting, as well as technical specifications and information. The manual focuses heavily on screenshots of the web and mobile applications. Datasheets and specification information can be found outside of the manual here.

5.2.7. Size

The Teconer RCM411 is a tube-shaped sensor with a scope on top of the sensor. The measurements and dimensions of the sensor are in Figure 13.

Figure 13. Teconer RCM411 Dimensions



5.3. High Sierra Mobile IceSight

High Sierra's Mobile IceSight was first available commercially in 2013 with the most recent revision being released in 2015. The IceSight uses an open-architecture data output that includes many various parameters, including: air temperature, relative humidity, surface temperature, six reportable surface state conditions (dry, damp, wet, slush, snow, and ice), and a surface friction coefficient. While this sensor does not have internal GPS data collection capability, High Sierra has worked with several vehicle controller companies to integrate GPS data from other sources.

The Mobile IceSight sensor has flexible mounting options and has a measurement range of 3 to 15 feet. A provided 15-foot cable can be adjusted to connect to the sensor wherever it is mounted. Depending on where the sensor is mounted and the angle at which it is oriented, the detection area of pavement surface can vary from 6 to 18 square inches, providing a large area of detection to ensure readings that reflect the entirety of the roadway surface. Recommended mounting locations for the IceSight include: inside the engine compartment, behind the cab on the driver's side, or on the roof of the vehicle facing the road.

The claimed useful life of the IceSight sensor is five to ten years. Current known users of High Sierra's Mobile IceSight include the Minnesota DOT and the New York State DOT.

Figure 14. High Sierra Mobile IceSight

5.3.1. Specifications

The voltage range for the High Sierra Mobile IceSight is 10 to 14 VDC and its power consumption is approximately 5 Watts. The operating temperature is -40 to 149ºF.

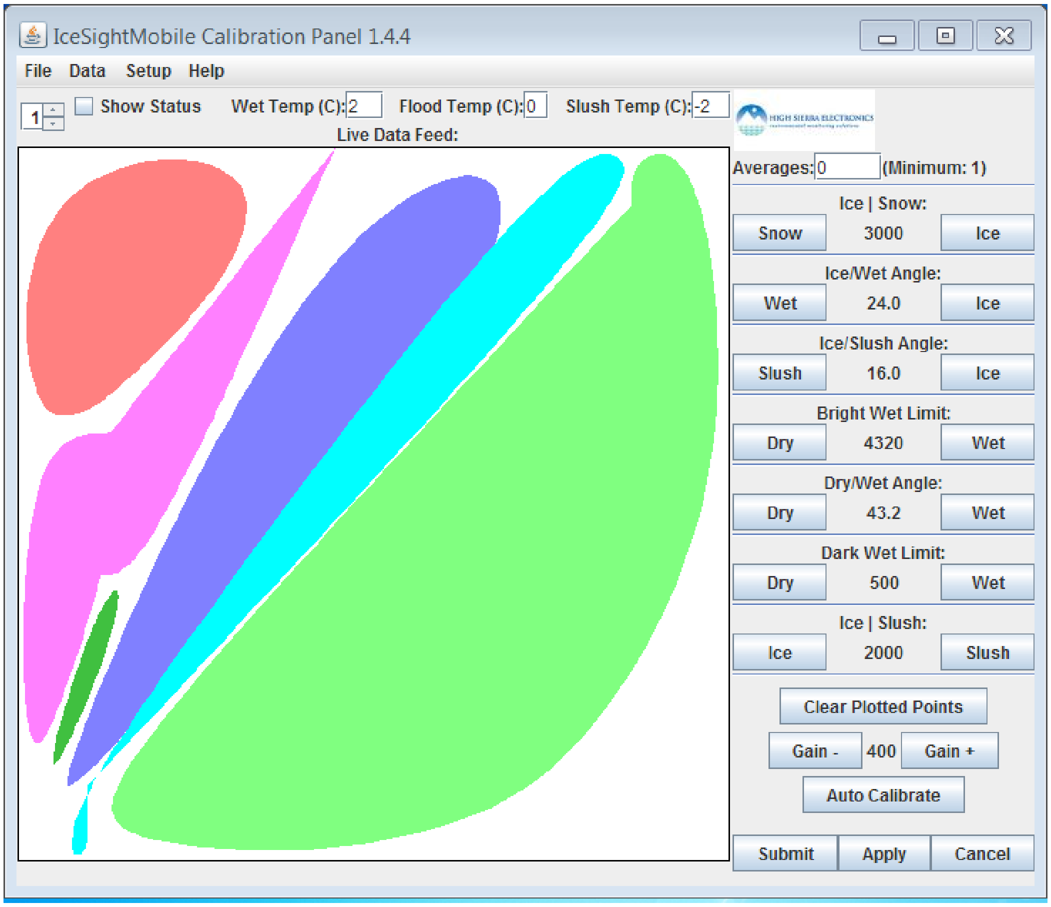
5.3.2. Connecting to Sensors

The High Sierra Mobile IceSight transmits data via RS-232, RS-485, and/or Wi-Fi communications. The sensor has a data output frequency of approximately once per second. The data can be sent to a Java-enabled readout or to an Automatic Vehicle Location (AVL) link. During the testing period, the IceSight was connected to a PC with a Java application via a Wi-Fi connection.

5.3.3. Interface

Unlike the other sensors in this study, the High Sierra Mobile IceSight was not connected to a mobile phone. Instead, a laptop computer with a Java application recorded information during the testing. The application shows a graph with colored "balloons" representing the different road statuses, e.g.; wet, ice, dry, etc. Points appear in the appropriate balloon as the sensor reports new data. Alongside the graph, data readouts and configuration tools are available, as shown in Figure 15. The interface is not as simple as some of the mobile applications but provides more technical information and requires little or no interaction if the user is satisfied with the current configuration. It may be difficult for a vehicle driver to quickly discern the road status during a run if they are not familiar with the application.

Figure 15. High Sierra Mobile IceSight Java Application



1

Wet Temp (C): 2

Flood Temp (C): 0

Slush Temp (C): -2

Averages: 0 (Minimum: 1)

Ice | Snow: 3000

Ice/Wet Angle: 24.0

Ice/Slush Angle: 16.0

Bright Wet Limit: 4320

Dry/Wet Angle: 43.2

Dark Wet Limit: 500

Ice | Slush: 2000

Gain: 400

5.3.4. Calibration

The High Sierra Mobile IceSight manual contains calibration instructions, but factory calibration may be available if the sensor mounting height and angle are known at the time of ordering. If the device is not factory calibrated or needs to be recalibrated, it is possible to do so by ensuring the device is clear of debris and by following the instructions in the manual.

5.3.5. Cleaning and Maintenance

The High Sierra Mobile IceSight should be checked periodically to ensure the lens is clear and reading conditions correctly. If the sensor is dirty, use a gentle, damp cloth with mild detergent to clean the lens. Though not written expressly in the manual, periodic checks of mounting, cables, screws, etc. are recommended. High Sierra also offers an annual service and maintenance plan option for an additional cost.

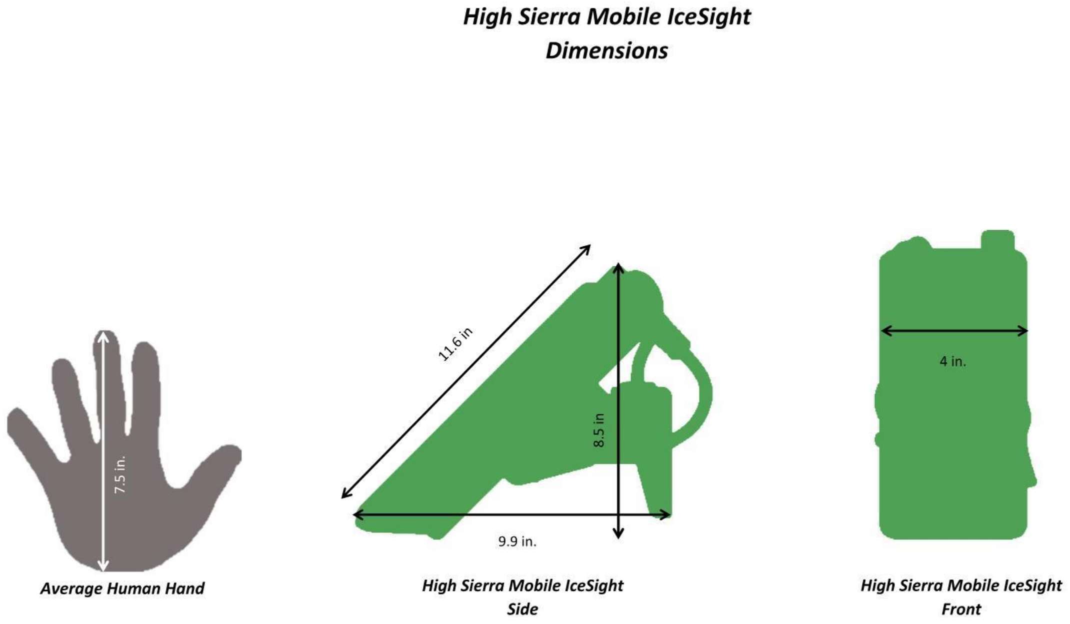
5.3.6. Manual

The High Sierra Mobile IceSight manual is 29 pages long and focuses on mounting information and sensor output. Technical information including specifications, operation, maintenance, and troubleshooting is also included. The manual can be found here.

5.3.7. Size

The High Sierra Mobile IceSight is a rectangular shaped sensor, around a foot long and four inches wide. Its dimensions are shown in Figure 16.

Figure 16. High Sierra IceSight Dimensions



5.4. Vaisala DSP310

Vaisala's DSP310 is the mobile edition of its DSC-111 road weather sensor. It has the capability to measure and report five surface state conditions, the pavement surface temperature, a friction coefficient, ambient air temperature, dew point, humidity, and water/ice/snow layer thicknesses. The five reportable surface state conditions include: dry, moist, wet, snow, and ice.

The DSP310 utilizes three different sensors to collect all the reported information. The DSP101 infrared sensor needs to be mounted with a clear view of the road for pavement temperature collection. The HMP-155 should be mounted away from any vehicle heat or exhaust to ensure accurate ambient air data collection. The DSC-111 points down at the road surface and should be mounted between 1.5 to 3 meters from the road surface. The typical mounting angle is approximately 45 degrees to parallel with the ground. Sensors are provided with a five-meter cable for information transfer back to the central controller.

It should be noted that Vaisala is currently in development of a replacement sensor for the DSP310. Field testing for the new Vaisala device is taking place with selected state agencies in the 2018-2019 winter season.

Figure 17. Vaisala DSP310

5.4.1. Specifications

The Vaisala DSP310 requires an input voltage of 10 to 33 VDC with an input current typically between 0.8-1.5A and a maximum of 10A. The power consumption ranges from 15-72W. The outside operating temperature range is -40 to 140ºF with an operating relative humidity of 0 to 100%.

5.4.2. Connecting to Sensors

The Vaisala DSP310 sends information back to a central processor which then displays the data on a smart phone device. The DSP310 reports at a frequency of about one measurement per three seconds. Data can also be sent through the phone's mobile network to Vaisala's road weather management software or to other MDSS systems as needed. Required upload speed is around one kilobyte per minute.

5.4.3. Mobile Interface

The Vaisala DSP310 mobile application contains many customizable options. The menu screen, shown in Figure 18, consists of submenus that allow the user to view past data and configure the application and sensors. The rest of the screens are "measurement screens," which display some combination of the air temperature, relative humidity, dew point, pavement temperature, and surface condition. The displayed variables can be changed in the settings, along with their "alert" threshold, which is the value(s) at which the text turns red. An example of one of the measurement screens is shown in Figure 19.

Figure 18. Vaisala DSP310 Menu Screen

Figure 19. Vaisala DSP310 Measurement Screen

Grip 0.27

Surface State Snowy

Water 0.00 mm

Snow 1.13 mm

Ice 0.10 mm

Surface Temp -1.5 °C

5.4.4. Calibration

Both the DSC111 and DSP101 components of the Vaisala require calibration. The DSC111 should be calibrated on a dry, homogenous surface like the surface most commonly measured. The DSP101 requires an ice bath to be created of chipped ice and cold water to calibrate. Calibration should be done at the beginning of the season, following the instructions laid out in the manual.

5.4.5. Cleaning and Maintenance

The Vaisala DSP310 should be checked periodically to ensure the lens is clear and reading conditions correctly. If the sensor is dirty, use a gentle, damp cloth with mild detergent to clean the lens. Check mounting, cables, screws, etc. regularly for looseness or damage. The Vaisala DSP310 requires a yearly filter change in the humidity probe and a yearly calibration of the probe at Vaisala's lab.

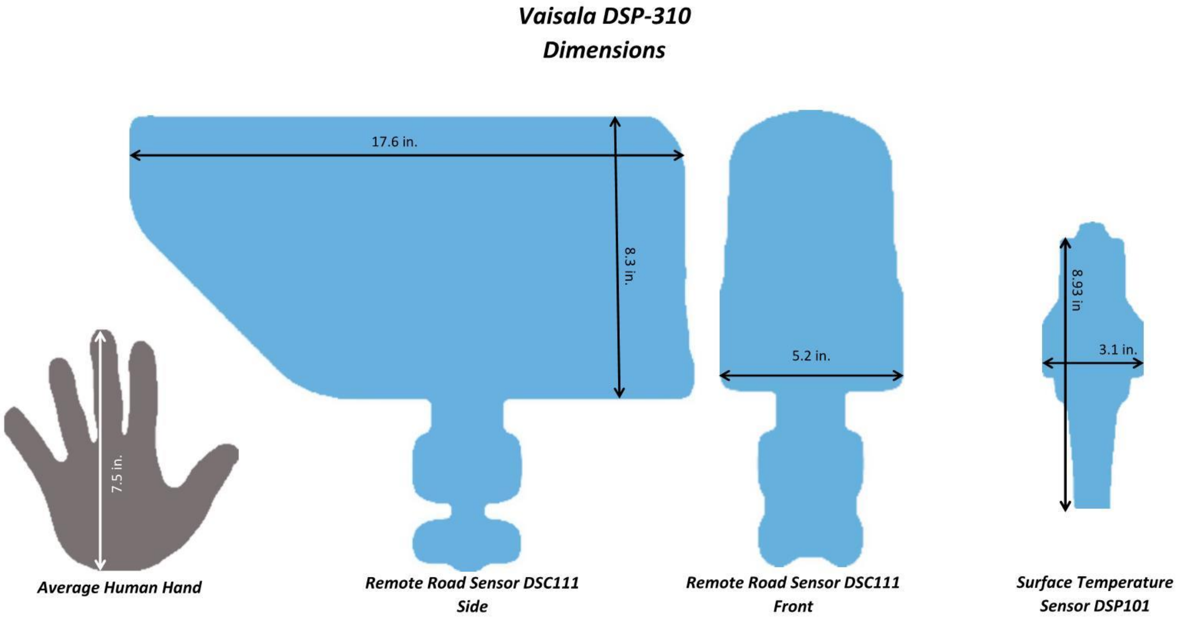
5.4.6. Manual

The Vaisala DSP310 manual is 114 pages, including 72 figures and 33 tables. The manual includes a product overview, installation instructions, operation instructions, maintenance practices, troubleshooting, and technical data. Most of the manual content is about operation. The manual is no longer listed on the website, but a data sheet can be found here and manuals for newer products are available.

5.4.7. Size

The Vaisala sensors consist of a remote road sensor, the DSC111, and a surface temperature sensor, the DSP101. These sensors are mounted separately, and the dimensions are shown in Figure 20.

Figure 20. Vaisala DSP310 Dimensions



Chapter 6. Test Plan and Procedure

An Evaluation Test Plan was developed and approved by the Clear Roads Project Committee in August 2017. To best measure and assess the various components of each sensor, the test plan divided testing into two phases. Phase I consisted of testing in a closed environment, the MnROAD test facility, to compare sensor data against baseline readings. Phase II consisted of testing in "real-world" conditions in the Twin Cities Metropolitan Area on several different road types and focused on comparing sensors' data against each other.

6.1. Phase I - Baseline Testing in Closed Environment

6.1.1. Test Methodology

Phase I focused on sensor parameter accuracy with testing conducted on the Minnesota Department of Transportation's MnROAD test track. Testing was performed over four different pavement Wtypes, including: tined concrete, aggregate, asphalt, and chip seal. This phase compared readings for surface temperature, air temperature, relative humidity, and water film height between the sensors and baseline reference devices. Sensors were acclimated to outdoor temperature and humidity levels before observations were recorded. A thermocouple was used as a baseline for pavement surface temperature. Baseline measurements for surface state condition were taken using qualitative observations. A baseline data source for pavement friction could not be acquired for this project, so no baseline for friction was included.

Figure 21. Aerial View of MnROAD Test Facility

6.1.2. Baseline Sensors

An Omega OM-73 device measured baseline values for air temperature and relative humidity and an Omega OM-74 device was used to establish surface temperature baselines. Measurements were taken while the test platform was stationary to allow the baseline reference devices to make direct contact with the pavement and readings to stabilize. Because surface conditions (dry, damp, snow, wet, etc.) are subjective and each sensor uses unique algorithms to detect the surface state, they were compared to a visual assessment of the pavement at the same spot checks.

To establish a baseline for water film thickness, a wet film comb was utilized. However, to establish the water film height, the wet film comb must be measured on a level, smooth surface. The unevenness of the pavement prohibited the comb from taking any accurate measurements. The wet film comb was used later to compare the sensors' measurements of water films on a smooth Plexiglas surface laid over a concrete floor.

A total of 35 individual readings on 4 different pavement types were taken during Phase I. For air temperature, surface temperature, and relative humidity, the average percent error was used to rate the performance of the sensors. The percent error is given by the following equation:

$$Percent\ error = \frac{|Baseline\ Value - Measured\ Value| * 100}{Baseline\ Value}$$

Qualitative observations were used to establish surface state conditions. The number of times sensor readings matched the visual assessment was used to rank performance.

6.2. Phase II – Live Traffic Testing

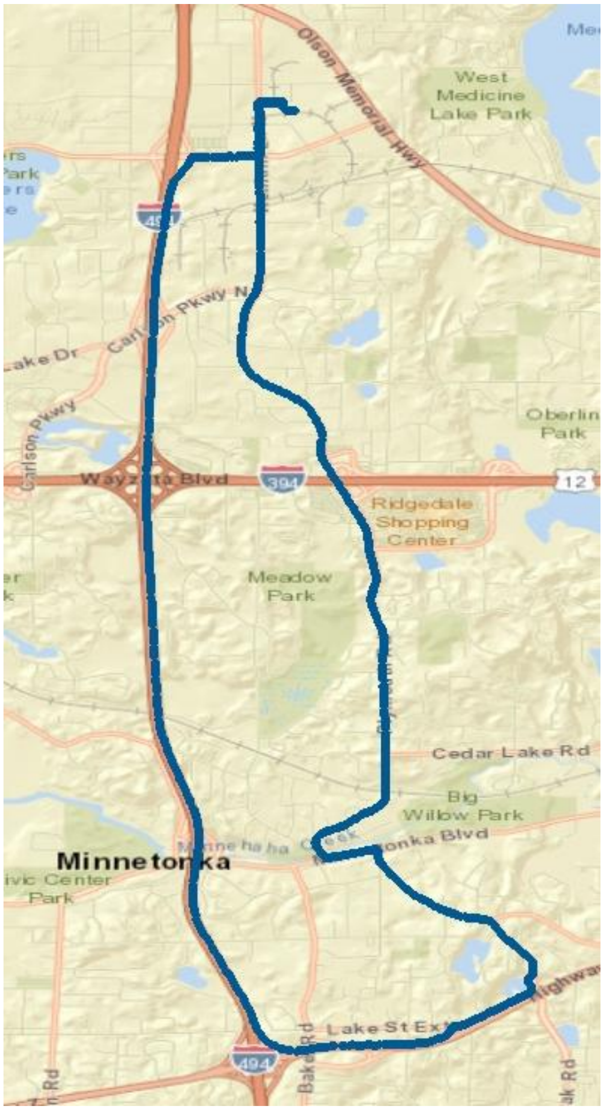
6.2.1. Test Methodology

Phase II tests were conducted on a predetermined, live-traffic route in the Twin Cities Metropolitan Area (see Figure 22). The test route included local, county, state, and interstate roadways with a mix of asphalt and concrete pavements as well as single, two, and three-lane facilities. These tests were conducted with the test platform in motion at prevailing traffic speeds to simulate a deployed sensor. During Phase II, 20 runs were made on the test route, producing over 90,000 total data points for all sensors.

Comparisons to baseline sensors were not used in Phase II as it was not possible to stop in live traffic for a baseline sensor to acclimate with conditions or make contact with the pavement. Therefore, Phase II focused on relative differences and consistencies between sensors.

While government sites such as the National Weather Service (NWS) provide air temperature and relative humidity information, the data is given only as a daily overview and weather stations are often far from testing locations. As a result, data from the crowd-sourcing weather site Weather Underground was used. Weather Underground data is uploaded from independent, privately-owned sensors approved by the organization. Data is recorded at shorter intervals than the NWS and is used as approximate relative humidity and air temperature values for a run. The weather underground data is used as a reference point rather than a precise baseline.

Figure 22. Phase II Testing Route



Chapter 7. Trailer Construction and Sensor Installation

To best accomplish the goal of comparing one sensor to another, a trailer design was developed which situated sensors in close proximity to one another so that each sensor was detecting the same area of pavement. As part of the project development and planning process for the field evaluation, it was noted that agencies would like to know more about the installation and mounting procedures required for each sensor. Since this project required simultaneous data collection of the same area for all sensors, installations on the trailer did not always match the procedures recommended by the sensor vendors. However, the proper mounting techniques and methods were followed as closely as possible with special modifications being made to the trailer to accommodate various mounting attachments.

7.1. Trailer Construction

SRF Consulting had an existing five-foot by ten-foot utility trailer available when this project began. The trailer was modified by removing the tailgate and installing a framed structure to help support the mounting of sensors at adjustable heights. The framed structure was heavily secured to the trailer to ensure that minimal vibration beyond that of the trailer rolling on the surface of the pavement affected the sensors. While the vibration experienced from a trailer is often much higher than that of a passenger vehicle, it is likely less than what a snowplow in operation would experience. Sensor installation went smoothly, in part because sensor vendors were extremely accommodating and helpful in providing any extra materials needed to secure their mounts to the trailer structure. To house the power supply and other various equipment, a large plastic cargo bin was installed at the front of the trailer. A cutout was made in the rear of the container for cables to enter and exit with a damper and lid to reduce water intrusion into the box. The trailer utilized a standard 50mm hitch and was towed using one of SRF's company pickup trucks for the duration of the field evaluation. All sensors were mounted on height-adjustable cross-supports to facilitate the testing of sensors at various heights.

Figure 23. Trailer Without Sensors

7.2. Sensor Mounting

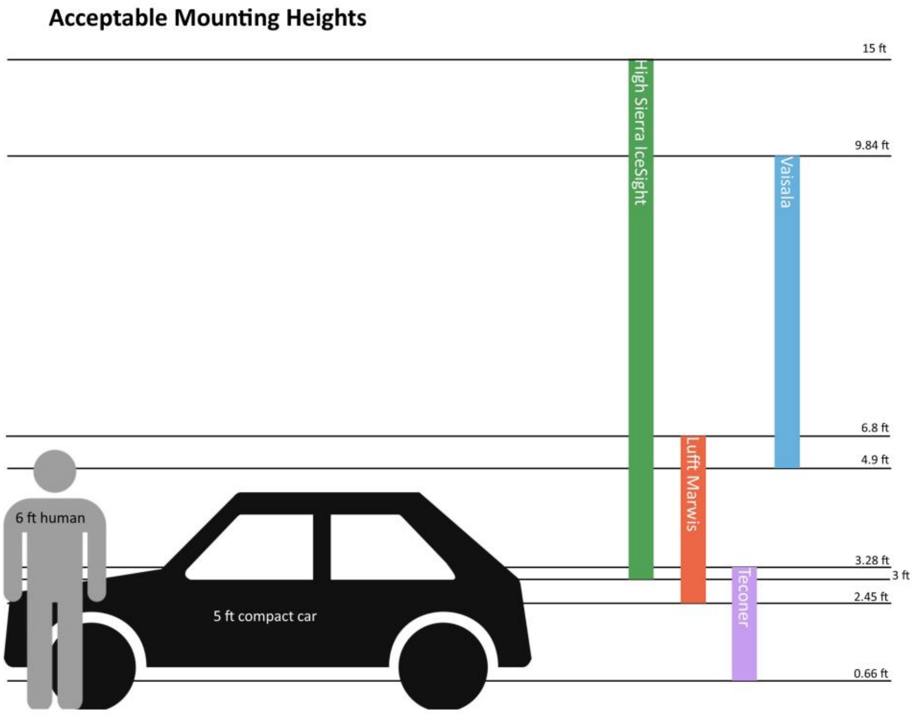
Each sensor was provided with one or several means to mount equipment to various types of vehicles. Some sensors provide non-intrusive mounting options such as suction cups while others required direct connection to various points on the vehicle. Table 2 identifies the location and attachments recommended/provided by each sensor vendor:

Table 2. Recommended Sensor Mounting Location and Method

	High Sierra	Lufft	Teconer	Vaisala
Mount Location	Driver Side Rear Window	Roof	Trailer Hitch	Roof
Mount Type	Mounting Bracket	Suction Cups	Ball Joint	Suction Cups

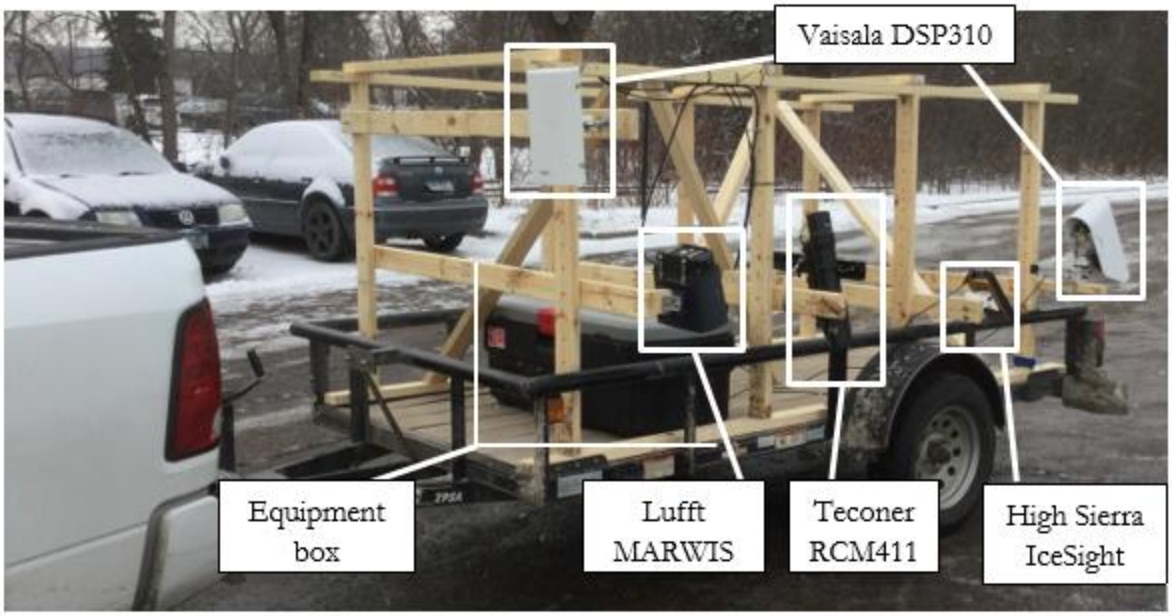
Each vendor identified several parameters which had to be met when mounting their sensor over the roadway. Most had identified specific mounting height ranges, and all had limitations in the distance the sensor would communicate with the user interface (via Bluetooth, WiFi, etc.). Figure 24 shows the acceptable mounting heights identified for each sensor.

Figure 24. Acceptable Mounting Heights for Mobile Sensors



Each sensor was mounted as close to the recommended procedure as was possible. Wooden boards served as replacements for vehicle roof racks or other intrusive mounting methods. The Teconer RCM-411 required a trailer hitch ball, so a hitch was mounted at the appropriate level on the trailer structure and the sensor mount attached. The most challenging part of mounting each sensor was finding methods to ensure sensors were secure and would not be affected by excessive vibration. Both the Teconer and Vaisala sensors required additional supports after it was discovered that vibrations caused both sensors to rock out of their assigned areas. Through the trailer construction and sensor mounting process, it was determined that a strong recommendation for any sensor purchase would be to check and secure attachments prior to each trip or run. As the value of each sensor is nearly $10,000, it is important that extra care is taken to ensure no parts are loose or have the potential to fall. Figure 25 shows the final trailer construction with all sensors mounted.

Figure 25. Trailer with Mounted Sensors



Chapter 8. Phase I – Baseline Testing in Closed Environment

Testing in Phase I followed the procedures outlined in the evaluation test plan developed earlier in the project. Six test runs were performed at the MNROAD pavement research test facility with various types of pavement and differing surface conditions. The summary below breaks out the results of all runs by parameter measured to best report the performance of each sensor. For each parameter, the sensor with the lowest percent error has its results bolded and underlined.

8.1. Phase I Test Results Summary

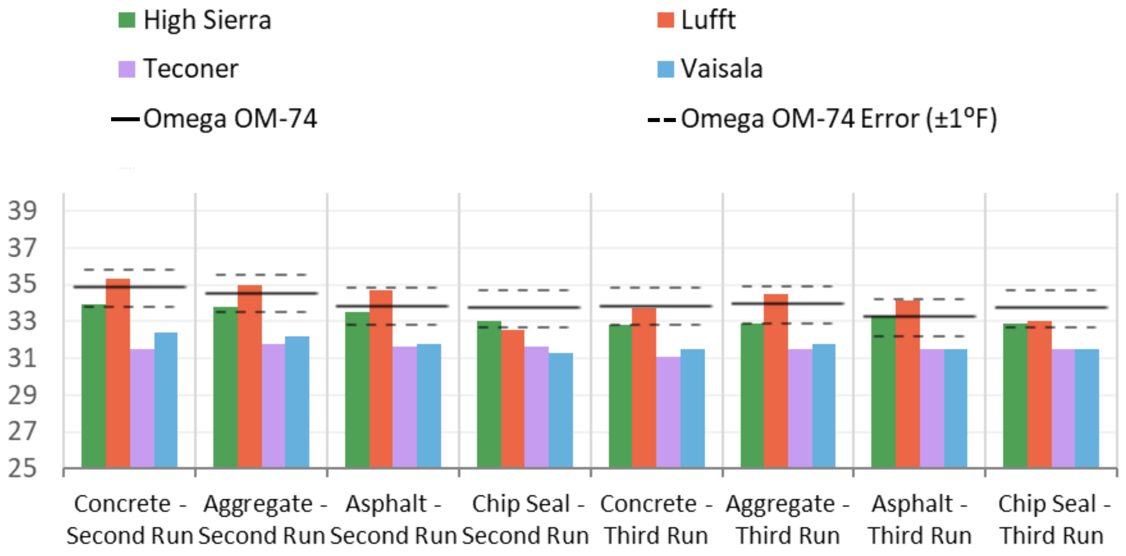
8.1.1. Air Temperature

When comparing sensor and baseline data for air temperature and relative humidity, it was observed that all sensors were within a range of 1-3°F, once normalized (see 0). When compared to the baseline measured by the Omega OM-73, the average percent error for all four sensors falls below 15% (see Table 3). None of the sensors had their average error fall in the 1-3% range desired by the majority of Clear Roads agencies surveyed. The Lufft MARWIS sensor had the lowest average percent error from the baseline readings taken in Phase I, with a value of 3.8%. The Teconer sensor had the highest percent error at 14.6%.

Table 3. Air Temperature Percent Error by Sensor

Air Temperature	Sample Size	High Sierra	Lufft	Teconer	Vaisala
Average % Error	29	6.9%	**3.8%**	14.6%	11.7%
Average Error in °F	29	2.55°F	**1.39°F**	5.50°F	4.44°F

Figure 26. Example Air Temperature by Sensor – March 6th (MNROAD)



8.1.2. Surface Temperature

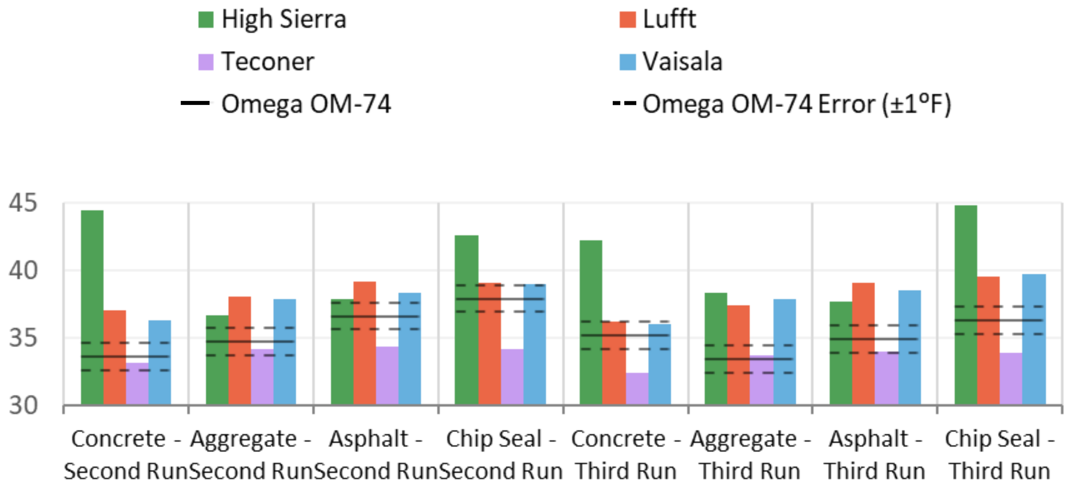
Sensor performance was compared on four different pavement types in Phase I, including: concrete, asphalt, aggregate, and chip seal. Nine baseline measurements were taken for each of the pavement types, except chip seal, which only had two baseline measurements due to other, external testing by MnDOT rendering that section of pavement unavailable except during the March 6th test runs.

The percent error for each device was calculated using the Omega OM-74's readings as the baseline surface temperature measurement (see Table 4). All devices averaged under 10% error for surface temperature, with the Lufft MARWIS having the lowest percent error, followed by Vaisala, Teconer, and High Sierra. The MARWIS had the lowest error for tined concrete and chip seal surfaces. The Vaisala device performed the best on aggregate and asphalt surfaces. While the percent error on different pavement types were similar overall, High Sierra's IceSight had percent errors much higher than the other sensors on concrete and chip seal. The High Sierra, Vaisala, and Lufft sensor readings were generally higher than the Omega OM-74 temperature, while the Teconer values were consistently below the baseline (see Figure 27).

Table 4. Surface Temperature Percent Error of Sensor by Pavement Type

	29		**5.6%**		5.8%
	29		**2.04°F**		2.07°F
	9		**3.7%**		5.5%
	9		7.0%		**5.7%**
	9		6.1%		**5.8%**
	2		**6.0%**		6.1%

Figure 27. Example Surface Temperature by Sensor – March 6th (MNROAD)



It was observed that when the pavement type changed (e.g. asphalt to concrete), there was a discontinuity in surface temperature readings (see Figure 28and Figure 29). Spikes would also occur if there was a person within two feet of the sensor, such as the readings taken around 2100 seconds in Figure 28 and photographed in Figure 29. Values would quickly return to the ambient value once the person left the area.

When not on traditional pavement, such as a crack-sealed surface, the variability between sensor readings was greater. This may indicate that some sensors are affected by different types of pavement surfaces, as shown in Figure 29. Surface temperature also tended to vary by greater amounts when sensors were driven over a small area of pavement where the surface condition changed, such as a puddle or patch of ice. Depending on how each sensor adapts to these variations and the frequency of measurements taken, data fluctuations vary in magnitude between sensors.

Figure 28. Example Surface Temperature from February 23rd, 2018 (MNROAD)

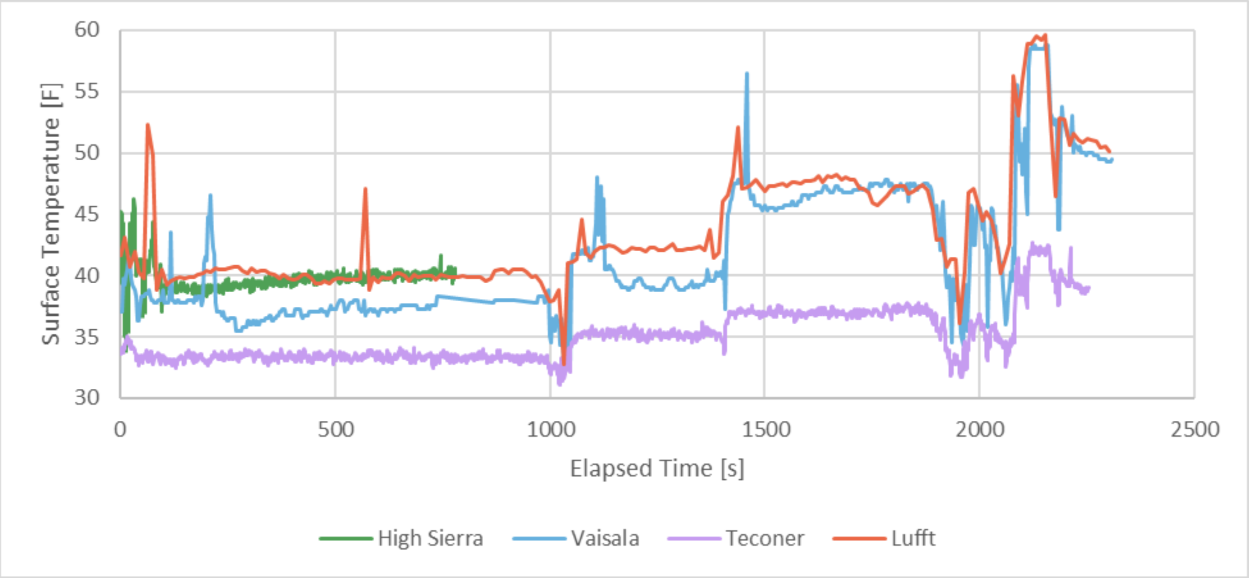


Figure 29. Surface Conditions at Surface Temperature Discontinuities

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T=500 seconds

T=1400 seconds

T=2100 seconds

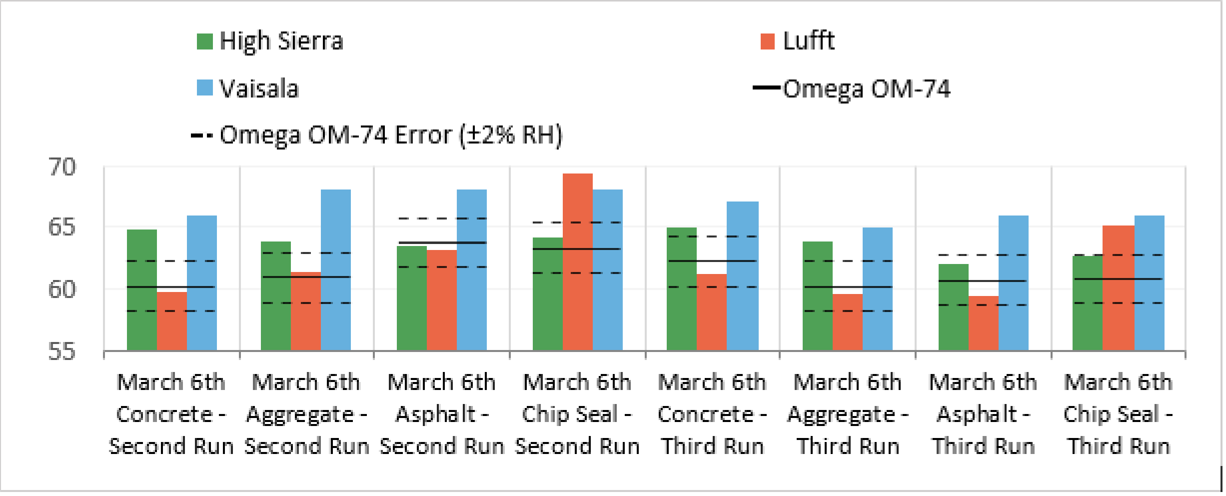
8.1.3. Relative Humidity

Relative humidity is measured by Vaisala, Lufft, and High Sierra. Teconer offers the ability to measure humidity as an add-on feature, but a device with that capability was not available at the beginning of the testing period. Compared to the baseline measured by the Omega OM-73, Lufft had the lowest percent error of the three devices (see Table 5). The Vaisala and High Sierra devices consistently measured humidity above the baseline value (see Figure 30). None of the three sensors that measure humidity had a percent error within the desired 1-3% range given by Clear Roads survey respondents.

Table 5. Relative Humidity Error by Sensor

Relative Humidity	Sample Size	High Sierra	Lufft	Teconer	Vaisala
Average % Error	29	13.2%	**9.2%**	n/a	15.5%
Average Error in % RH	29	7.58% RH	**6.48% RH**	n/a	8.38% RH

Figure 30. Example Relative Humidity by Sensor – March 6th (MNROAD)



8.1.4. Surface Conditions

All four sensors report a qualitative surface condition. Each employs a proprietary calculation to determine the surface state condition based on the measured friction, surface temperature, and water film thickness. Table 6 outlines the general results observed throughout the evaluation. Red text indicates a reported condition different from what was expected based on observations, including touching the pavement to determine dampness or wetness. Attempted measurements were taken with a wet film comb, though were unreliable due to the wet film comb's inability to measure accurately on rough surfaces.

Table 6. Surface State Condition – Observed vs. Reported Results

Date	Pavement Type	Observation	Sensor				Photo
			Vaisala	IceSight	Lufft	Teconer	
2/20	Concrete (tined)	Snow	Snowy	Snow	Ice/Snow	Ice/Snow	
	Aggregate	Snow	Snowy	Snow	Ice/Snow	Ice/Snow	
	Asphalt	Snow	Snowy	Snow	Ice/Snow	Ice/Snow	
2/23	Concrete (tined)	Damp/Wet	Wet	Wet	Wet	Wet	
	Aggregate	Wet	Wet	Wet	Wet	Wet	
	Asphalt	Wet	Wet	Wet	Damp	Wet	
3/2	Concrete (tined)	Dry	Dry	Dry	Dry	Dry	
	Aggregate	Dry	Dry	Dry	Dry	Dry	
	Asphalt	Dry	Dry	Dry	Dry	Dry	
3/2	Concrete (tined)	Dry	Dry	Dry	Dry	Moist	
	Aggregate	Dry	Dry	Dry	Dry	Dry	
	Asphalt	Dry	Dry	Dry	Dry	Dry	
3/5	Concrete (tined)	Snow	Snowy	Snow	Ice/Snow	Snow	
	Aggregate	Snow	Snowy	Snow	Ice/Snow	Snow	
	Asphalt	Snow	Snowy	Snow	Ice/Snow	Snow	

Table 6. Surface State Condition – Observed vs. Reported Results

Date	Pavement Type	Observation	Sensor				Photo
			Vaisala	IceSight	Lufft	Teconer	
3/5	Concrete (tined)	Snow	Snowy	Snow	Ice/Snow	Snow	
	Aggregate	Snow	Snowy	Snow	Ice/Snow	Snow	
	Asphalt	Snow	Snowy	Snow	Ice/Snow	Snow	
3/6	Concrete (tined)	Damp	Wet	Wet	Wet	Damp	
	Aggregate	Damp	Wet	Wet	Wet	Wet	
	Asphalt	Damp	Moist	Dry	Wet	Wet	
3/6	Concrete (tined)	Wet	Wet	Wet	Wet	Damp	
	Aggregate	Damp	Wet	Damp	Damp	Wet	
	Asphalt	Damp	Wet	Dry	Dry	Wet	
	Chip Seal	Damp	Moist	Dry	Dry	Dry	
3/6	Concrete (tined)	Damp	Wet	Wet	Wet	Damp	
	Aggregate	Damp	Moist	Dry	Dry	Damp	
	Asphalt	Damp	Moist	Dry	Dry	Slush	
	Chip Seal	Damp	Moist	Dry	Dry	Damp	

Table 7 summarizes the number of correct surface state readings for each sensor. As the baselines were formed from human observations, they are inherently subjective.

Table 7. Number of Correct Surface State Readings by Sensor

Surface State	Sample Size	High Sierra	Lufft	Teconer	Vaisala
Number of Correct Surface State Readings	29	20	19	21	**24**

8.1.5. Water Film Thickness

Water film thickness is measured by the Vaisala, Teconer, and Lufft devices. A wet film comb was initially selected as a baseline measurement device but had difficulty measuring on traditional road surfaces due to the porous, rough nature of most roadways. To ensure precision, researchers determined that wet film combs should only be used on smooth surfaces. As such, the research teams conducted follow-up tests using a smooth Plexiglas surface placed over concrete. Two baseline readings were taken: the water thickness on the bare concrete garage floor and the dry, clean Plexiglas. Water was sprayed onto the Plexiglas until a film formed. The height measured by the film comb and the sensor was recorded. Five tests for each sensor at three water levels were taken, including thin (no water droplets forming), medium (some droplets beginning to form), and thick (many droplets but no pooling).

Table 8. Water Film Height Readings and Percent Error by Sensor

Vaisala			
Garage Floor [mm]		0	
Plexiglass [mm]		0.02	
Film Comb [mm]	Sensor [mm]	Sensor Reading - Water Film Height [mm]	Percent Error [%]
0.025	0.06	0.005	80.0
0.025	0.06	0.04	60.0
0.1	0.08	0.06	40.0
0.25	0.15	0.13	48.0
0.55	0.17	0.15	72.7
		Average Error in mm	**0.119 mm**
		Average % Error	**60.1%**

Teconer			
Garage Floor [mm]		0.05	
Plexiglass [mm]		0.25	
Film Comb [mm]	Sensor [mm]	Sensor Reading - Water Film Height [mm]	Percent Error [%]
0.025	0.42	0.17	580
0.025	0.53	0.28	1020
0.1	0.56	0.31	210
0.45	0.73	0.48	6.7
0.75	0.63	0.38	49.3
		Average Error in mm	**0.202 mm**
		Average % Error	**373.2%**

Lufft			
Garage Floor [mm]		0.025	
Plexiglass [mm]		0.174	
Film Comb [mm]	Sensor [mm]	Sensor Reading - Water Film Height [mm]	Percent Error [%]
<0.025	0.244	0.07	180.0
0.025	0.228	0.054	116.0
0.15	0.335	0.161	7.3
0.65	0.48	0.306	52.9
0.725	0.473	0.299	58.8
		Average Error in mm	**0.171 mm**
		Average % Error	**83.0%**

Vaisala had the lowest percent error of the three sensors (see Table 8). Teconer had the highest average percent error. Lufft and Teconer both had high errors at the thin water film heights but improved as the height of the water film increased. None of the sensors performed under the desired accuracy of Clear Roads survey respondents. It should be noted that although the percent errors are unusually high, they correlate to minimal differences in values (0.202 mm, a fraction of a millimeter, equates to a 373% error).

Chapter 9. Phase II – Field Testing in Live Traffic

Phase II testing was performed following the procedures developed in the evaluation test plan. Twenty test runs were performed on the identified live-traffic test route around the Twin Cities Metropolitan Area. Data was collected on various pavement surfaces, under varying conditions, and at different times/light levels to test the full array of possible conditions that sensors may encounter in real world applications. The summary below breaks out the results of all runs by parameter measured to best report the performance of each sensor.

9.1. Phase II Test Results Summary

9.1.1. Air Temperature

Air temperature is measured on all four devices. Overall, the tested devices appear to give very similar values for air temperature, with differences rarely exceeding more than 3 ^{0}F. The primary difference in performance is in how quickly the values converge on the ambient temperature when transitioning from a warm environment (60 ^{0}F) to a cooler one. In this regard, the Lufft MARWIS sensor performs better than the other sensors, although all converge on a similar temperature value within 10 minutes.

High Sierra’s Mobile IceSight records three values for air temperature: “primary”, “secondary”, and “tertiary”. Though the “secondary” air temperature is displayed by the provided software, the “primary” value is the measurement that most closely reflects the actual ambient air temperature. The “secondary” and “tertiary” values are used for the internal sensor temperature and calculations for other values. After contacting High Sierra about the display, they reported that a future firmware update will change the on-screen value to the primary air temperature. The Mobile IceSight is consistently the third quickest value to adjust to outdoor temperatures after being in the garage.

Vaisala’s DSP310 was often observed to reach ambient values for air temperature shortly after the MARWIS, and often produced the lowest minimum, median, and mean values for a given test run. Unlike the other sensors, the DSP310’s measurements did not gradually adjust to the outdoor temperatures, but instead, often recorded the warmer garage temperature for several minutes before sharply dropping to the ambient, outdoor temperature (see Figure 31 and Figure 32). Beyond this anomaly, the DSP310 was well within the maximum adjustment time of 15 minutes reported in its user manual.

The MARWIS generally adapts to new temperatures the quickest and has the lowest maximum temperature value for a test run (see Figure 31 and Figure 32). The manual specifies a 5 to 15-minute range to adjust to current ambient temperature, which was confirmed by field observations. The short adjustment period likely decreased its percent error, which was found to be the lowest of the four sensors evaluated in Phase I.

Teconer's RCM411 was observed to have the longest delay in reaching ambient air temperature values. The long delay likely contributes to its high average percent error from Phase I, which was the largest error of the four sensors. Its range is most often the widest of the four devices. However, the reported temperature appears to adjust at a more uniform rate than some of the other sensors (see Figure 31 and Figure 32).

Figure 31. Example Air Temperature Convergence (Low Temperature)

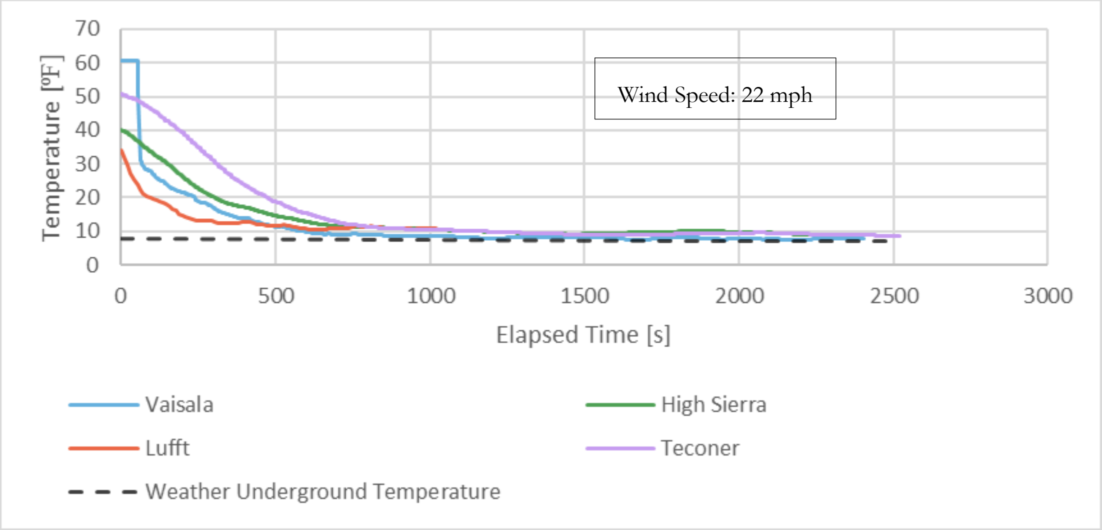
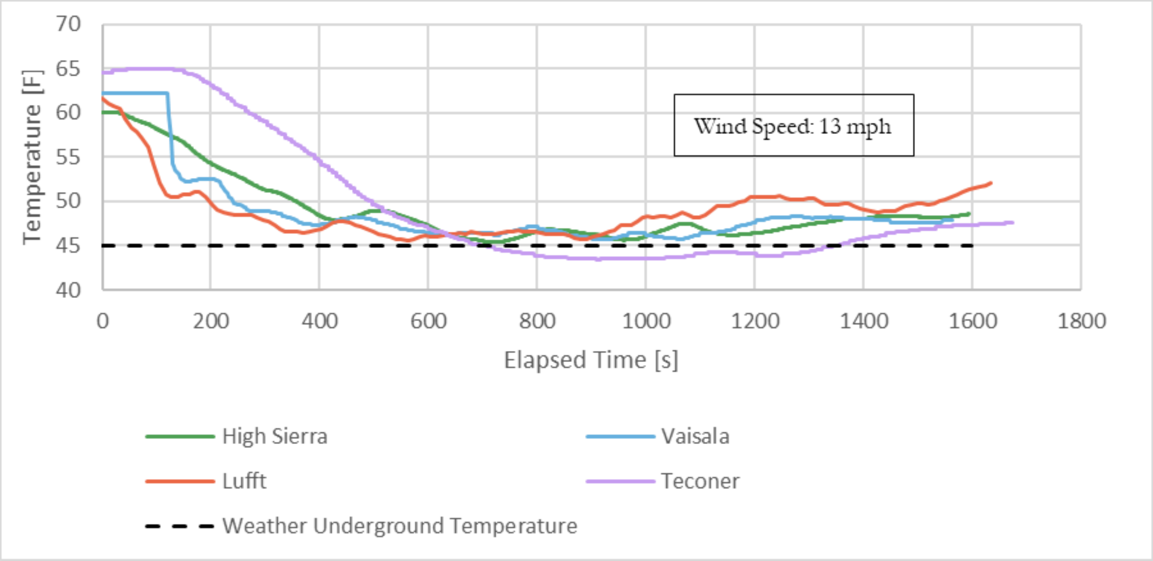


Figure 32. Example Air Temperature Convergence (High Temperature)

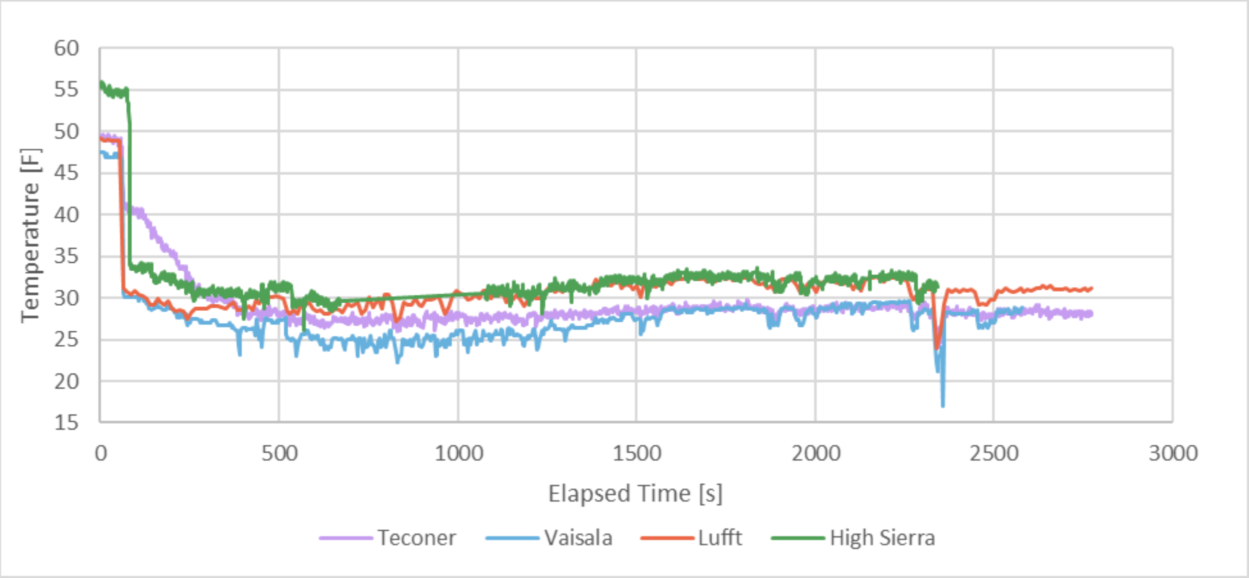


9.1.2. Surface Temperature

Each mobile sensor uses some form of an infrared sensor to measure and record pavement surface temperatures. While each device requires some time to adjust from garage to outside temperatures, most acclimate in less than five minutes. Temperature variances between devices tended to range within 5-10ºF from one another. While this range may seem large, it is important to remember that changes in the surface, such as small patches of ice or potholes, may drastically affect temperature in a small area.

The MARWIS sensor generally had the smallest range and the highest minimum for measured surface temperature. The MARWIS and Mobile IceSight's mean measured surface temperature were usually similar and higher than that of the Vaisala and Teconer units. The RCM411 appeared to require the most time to adjust and normalize surface temperature measurements from the garage to outdoor conditions. Vaisala's DSP310 most often had the lowest measured maximum and minimum surface temperatures, as well as the lowest median and mean.

Figure 33. Surface Temperature from January 22nd, 2018



Overall, trends were very consistent between sensors. However, a difference of only a few degrees can have a major impact on road weather maintenance decisions. Testing results from Phase I as well as individual agency needs and uses for surface temperature values should also be considered.

9.1.3. Relative Humidity

Reported relative humidity trended similarly between the three sensors which reported measurements. The reported humidity for Lufft typically started off as the highest value after leaving the garage and changed quickly. The Lufft sensor tended to drop below the readings from the other two sensors about 20 minutes into a run, then stabilized (see Figure 34 and Figure 35). It also tended to have a wider range than the DSP310 and the Mobile IceSight. If the sensors had at least ten minutes to adjust outside, Lufft started and stayed lower than the other two values. After Lufft had time to stabilize, values were typically within 10 percent of one another.

The DSP310 and Mobile IceSight increased slower than Lufft but stabilized faster (usually around 10 minutes) after leaving the garage. The values did not fluctuate as much as the Lufft readings, and the DSP310 trended higher than the Mobile IceSight.

Figure 34. Example Relative Humidity from January 19th, 2018

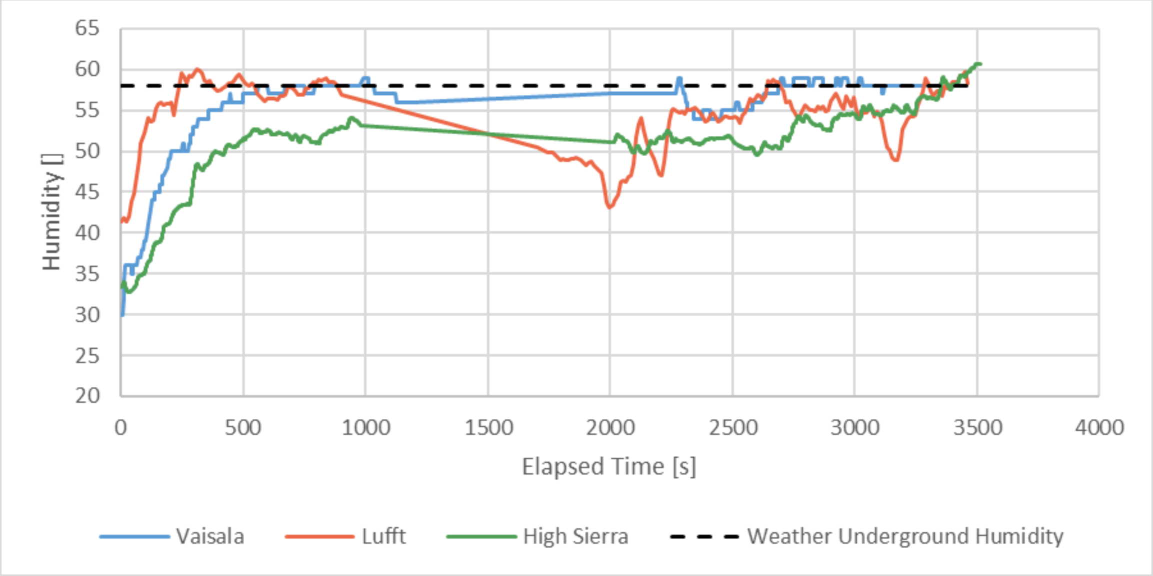
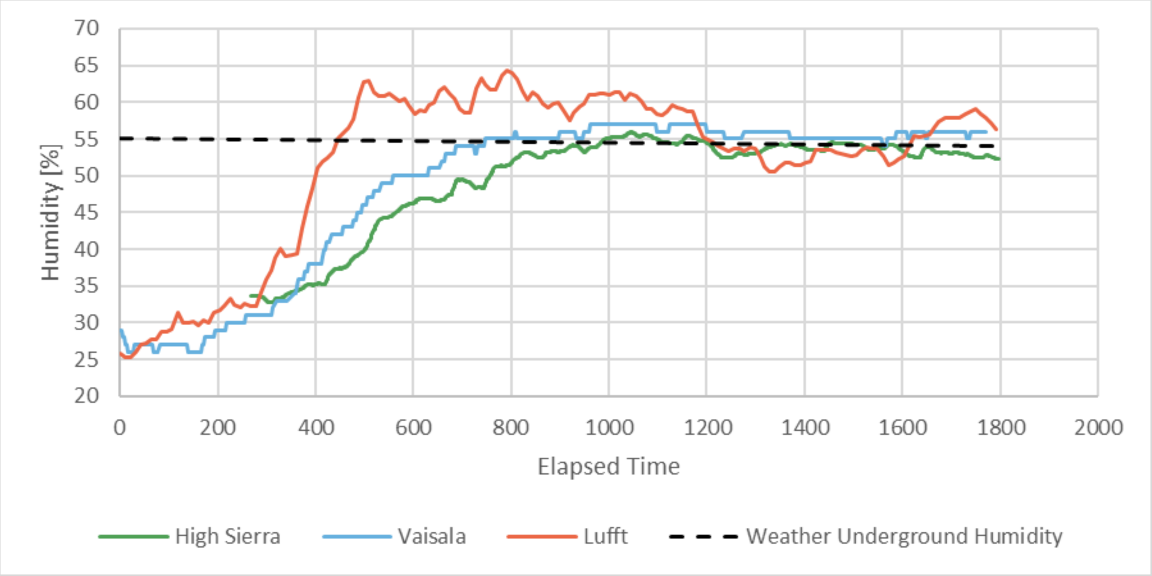


Figure 35. Example Relative Humidity from January 23rd, 2018



9.1.4. Water Film Thickness

Water film thickness is measured by three of the four sensors: Vaisala, Teconer, and Lufft. Vaisala and Lufft both use spectroscopic sensors for water film height. Vaisala also measures ice and snow height. While Teconer does not explicitly state its method for measuring water film height, it is assumed to be similar to the other sensors.

The three sensors display similar trends in values, though often are a consistent value apart, such as the ~0.15mm gap between the sensor readings shown in Figure 36. The difference between the readings increases considerably when the water film height is large, like the areas shown by spikes in Figure 38. These wide ranges in values may be due to mechanical or calibration differences between the sensors.

During testing, Vaisala typically had the lowest median and mean measurements out of the sensors that measure water film height. These low values may be due to Vaisala's distinct measurements for the layer thickness of water, ice, and snow. Teconer and Lufft may read snow or ice as water, and Vaisala may read water as snow or ice, contributing to the difference. Teconer regularly had the highest maximum water film height measurements during a trial (see Figure 36 and Figure 38). It tended to jump around more than Vaisala or Lufft readings when the water film levels were observed to be very low. Lufft's readings were similar to Teconer's, but with a smaller range. Typically, Teconer's range was twice that of Lufft's during the same trip.

Figure 36. Example Water Film Thickness from January 22nd, 2018

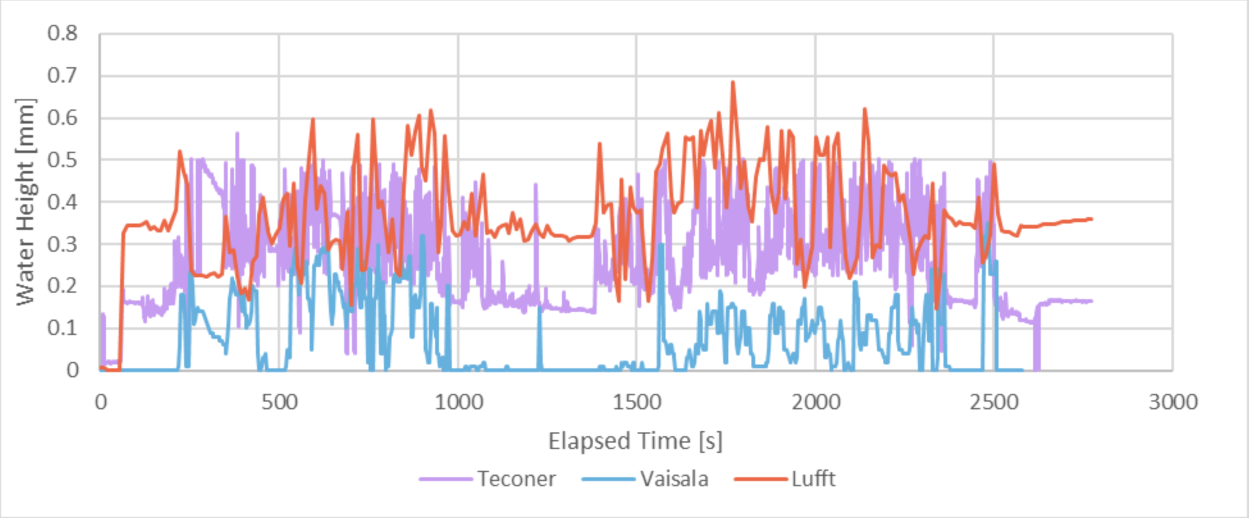


Figure 37. Photos of condition changes at t=2000 and t=2700

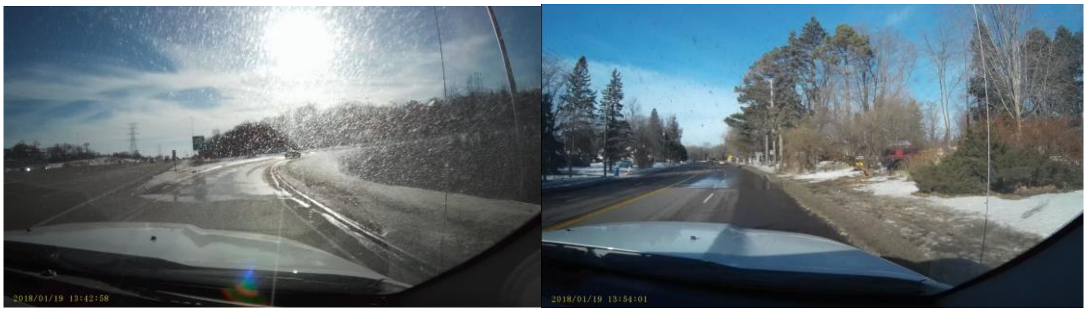
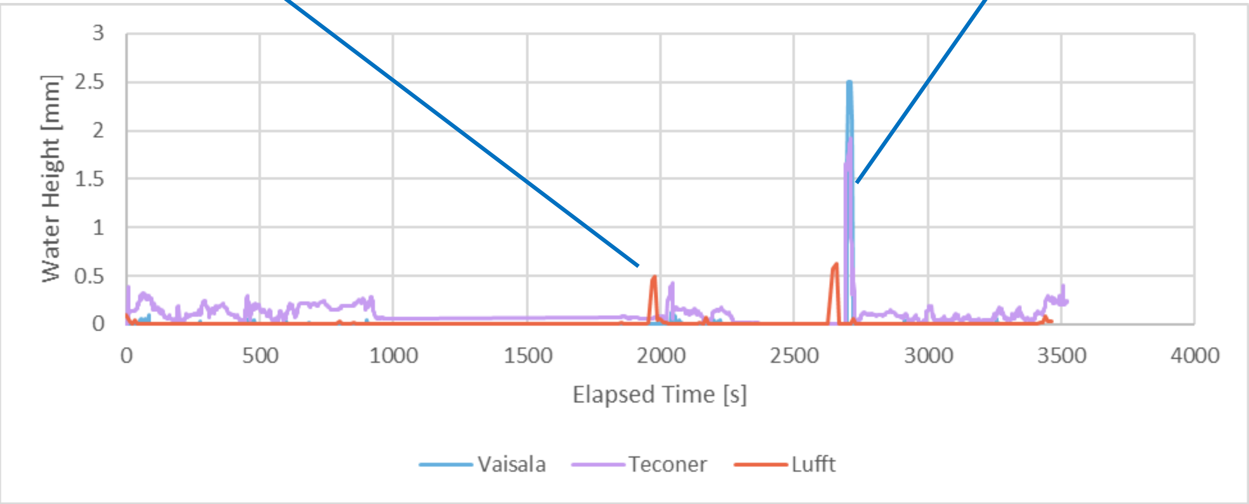


Figure 38. Water Film Thickness from January 19th, 2018



Like the other parameters measured, water film thickness readings exhibit similar trends across a test run. Large differences are reported occasionally, especially when water levels are higher than half a millimeter. While each agency has unique needs, most Clear Roads survey respondents reported they do not use water film thickness to influence their operations. Among the agencies that do use this data, the Colorado DOT implements water film thickness in an existing study.

9.1.5. Friction

Each device measures reflectiveness of the road or materials covering the road, then models a numerical value to represent friction. Surface friction is represented by a unitless number between 0 and 1, with 0 being a frictionless surface, and 1 being infinite friction. On a dry, indoor, concrete surface, all four devices reported a friction coefficient of approximately 0.81. On outdoor roadway surfaces, the readings varied considerably. In dry conditions, the values tended to be closely grouped. In wet, ice, or snow conditions, the range of values tended to widen. Increases and decreases in values tended to occur at the same time and place. Many tests, such as the example shown in Figure 41, show similar data readings for all sensors. When the vehicle drove over an icy patch, all sensors reported a drop in friction at approximately the same time. On other test runs, such as the one shown in Figure 39, large discrepancies appear between sensors. The models, methods, and calibration of each sensor are unique, which accounts for some of the discrepancies between sensors in the reported values.

Differences between devices are substantial, so they are described in individual sections below.

High Sierra Mobile IceSight

High Sierra's Mobile IceSight tends to give the lowest mean friction value of the four devices and appears to rapidly jump back and forth between two values (see Figure 39 and Figure 40). This could be due to a higher sensitivity or from the Mobile IceSight's more frequent data transmission rate of once every second. The Mobile IceSight also applies a hysteresis calculation, which is an averaged value used to smooth the data.

Vaisala DSP310

The Vaisala DSP310 gave the widest range in friction values for any single data collection run and tended to be the second highest value for any given point. Throughout testing, it often reported communication errors instead of friction readings due to poor signal strength between the sensor's base unit and the mobile device storing the data (see gaps in data in Figure 39). However, the actual distance between the base unit and mobile device did not exceed the manufacturer's recommendations.

Lufft MARWIS

Lufft's MARWIS generally presented the smallest range in friction values in any single test run (see Figure 39 and Figure 40), but usually gave the highest of the four measurements. As noted earlier, the MARWIS collects data at intervals between 0.1 to 5 seconds, but only reports recorded data every ten seconds. This data collection interval and the internal calculations conducted before reporting the data may factor into the smaller range and generally higher values, as low friction areas like patches of ice may not be recorded. A smaller recording interval increases the odds that these small areas will be recorded and therefore lower the friction readings overall.

Teconer RCM411

The RCM411's maximum value for each test is usually the lowest of the four devices, possibly indicating a more conservative approach to reporting friction values. The device manual mentions that the device is optimized to read friction on thin ice layers. The difference between the Teconer values and the other sensor readings may also come from a difference in precision, as the Teconer values mostly skip between only a few values but does so rapidly.

Figure 39. Example Friction from January 22nd, 2018

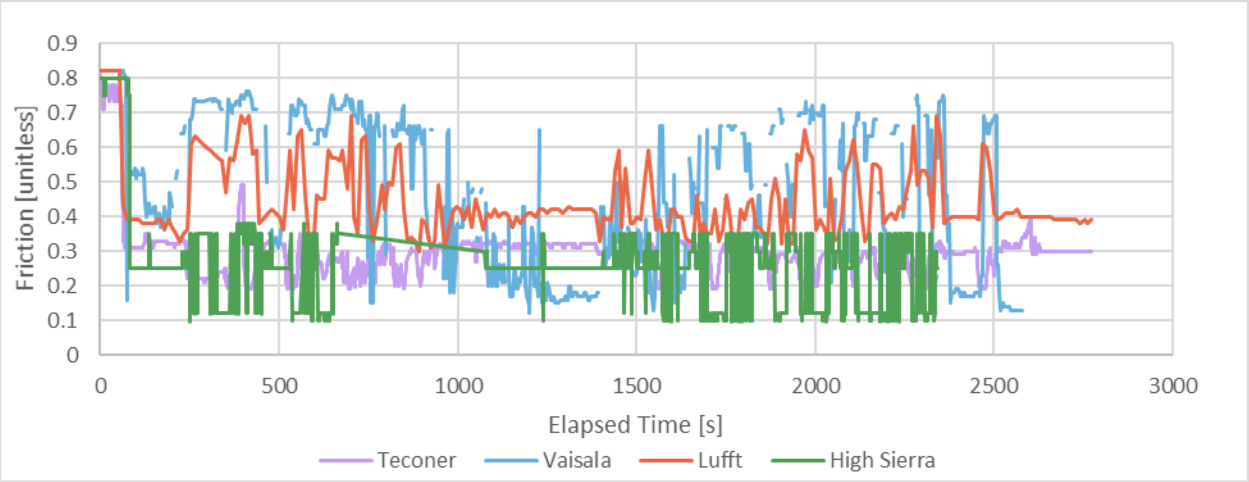


Figure 40. Example Friction from January 23rd, 2018

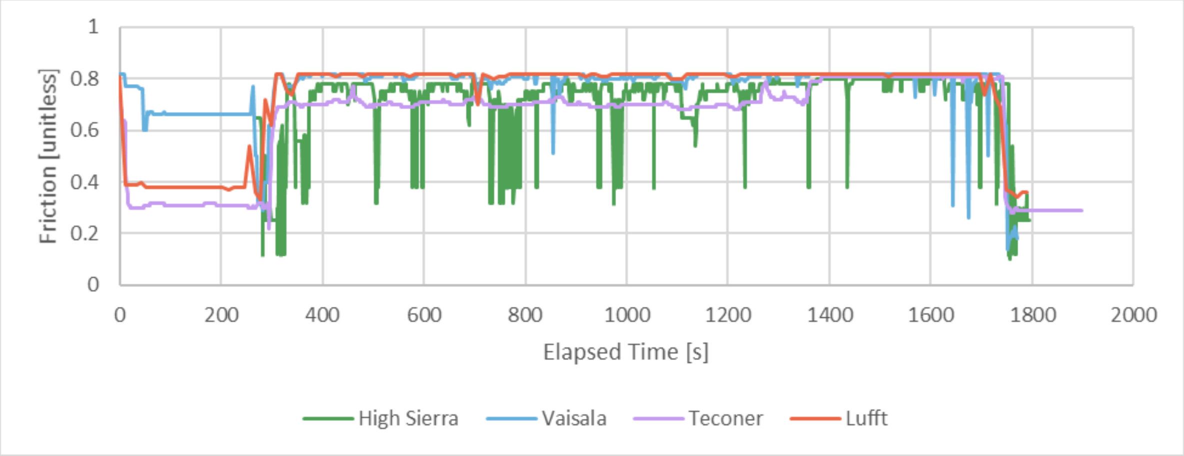


Figure 41. Friction from January 19th, 2018

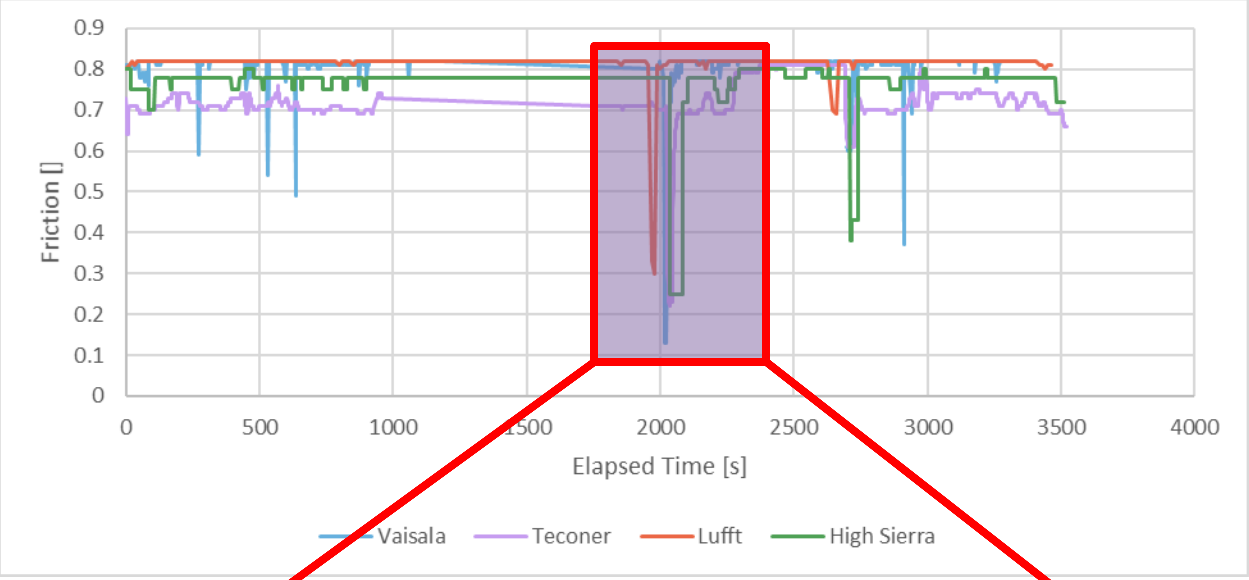
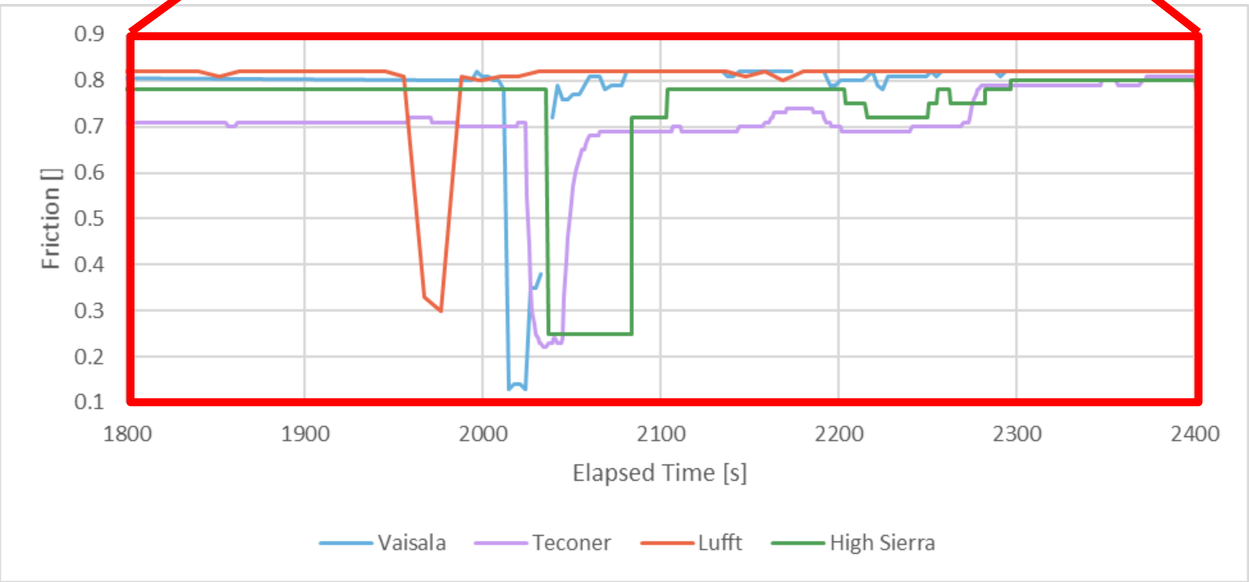


Figure 42. Example Friction from January 19th, 2018, from 1800-2400 s



Observed Friction Test Summary

Each of the sensors produced friction values that varied with observed roadway conditions. However, the values were not directly comparable. The DSP310 had the greatest range of values and the MARWIS the smallest, suggesting that measurements would need to be more closely calibrated to each other for more consistency in results. Since sensors were each either factory calibrated or calibrated per the manufacturer's recommendations, calibrating between devices was not considered to ensure the integrity of the data intended from each vendor. Raw values from each sensor also differ considerably, with some consistently reading near the top of the range and others consistently near the bottom.

Regardless of the actual value reported, the sensors tend to change readings based on observed conditions. This suggests that once readings are understood, each sensor could be used to provide a gauge of surface friction. Experienced users of a sensor would be able to detect unusual shifts in sensor readings and adapt operations. However, as reported in the 'Standards Development and Recommendations' section, it is recommended sensor manufacturers standardize and categorize their sensor data to improve use for agencies.

9.2. Accuracy – Expectations and Results

Prior to the testing task, Clear Roads agencies were surveyed about their desired level of accuracy for each measured parameter. Respondents were asked to choose from the following as their desired accuracy: Very Poor Accuracy (10%+ error), Questionable Accuracy (within 10% error), Acceptable Accuracy (within 5% error), Good Accuracy (1-3% error), and Excellent Accuracy (0-1% Error). Table 9 shows the percentage of respondents who chose each level of accuracy for each parameter.

Table 9. Desired Accuracy from Clear Roads Survey Respondents

		Parameter			
		Pavement Temperature	**Air Temperature**	**Relative Humidity**	**Water Film Height**
Desired Accuracy	**Very Poor Accuracy (10%+ error)**	0%	0%	0%	5%
	Questionable Accuracy (within 10% error)	0%	0%	6%	10%
	Acceptable Accuracy (within 5% error)	4%	9%	17%	**38%**
	Good Accuracy (1-3% error)	**61%**	**59%**	**67%**	**38%**
	Excellent Accuracy (0-1% Error)	35%	32%	11%	10%

Based on the testing performed and data collected, none of the sensors performed within the majority's desired accuracy for any parameter during the testing. The average percent error and preferred percent error are shown in Table 10. Bolded and underlined table items indicate the most accurate sensor for each parameter.

Table 10. Average Percent Error by Sensor and Parameter

		Parameter			
		Pavement Temperature	**Air Temperature**	**Relative Humidity**	**Water Film Height**
	Desired Accuracy	**1-3% Error**	**1-3% Error**	**1-3% Error**	
Mobile Sensor	**High Sierra**	9.6% Error	6.9% Error		
	Lufft	**5.6% Error**	**3.8% Error**		
	Teconer	8.3% Error	14.6% Error		
	Vaisala	5.8% Error	11.7% Error		**60.1 % Error**

While the discrepancy between desired and actual percent error is significant, it is important to note that when working with small numbers, a slight difference may give a large percent error. For example, a 0.5ºF difference when the exact temperature is 5ºF generates a 10% error. Teconer's average error of 373.2% for water film height (see Table 10) is an average error of only 0.202mm (Table 11).

Therefore, the average difference between the sensor measurement and the baseline measurement are reported in Table 11 with the parameters' units. In addition to the project testing that was performed, manufacturers also report accuracy values for each parameter of their sensor in the product manuals. This error margin reported by the manufacturers is included in Table 11.

Table 11. Average Error by Sensor and Parameter (in Parameter Unit)

	Pavement Temperature	Air Temperature	Relative Humidity	Water Film Height
High Sierra Test Runs	3.75°F	2.55°F	7.58%	N/A
Vendor Reported Lab Results	±2°F	±0.9°F	±3%	N/A
Lufft Test Runs	2.04°F	1.39°F	6.48%	0.171 mm
Vendor Reported Lab Results	±1.44°F	±0.9°F	±3%	±10%
Teconer Test Runs	2.94°F	5.50°F	N/A	0.202 mm
Vendor Reported Lab Results	±0.6°F	±0.6°F	N/A	±10%
	2.07°F	4.44°F	8.38%	0.119 mm
Vendor Reported Lab Results	±0.6°F	N/A	N/A	N/A

Testing results had errors much higher than both the manufacturer reports and the desired survey results. After testing was completed and the preliminary findings were shown to the Clear Roads Committee, some concern arose that the error was much higher than expected. However, the committee also recognizes the limitations of available technology in real-world roadway conditions. Therefore, it is recommended that manufacturers continue to work on improving accuracy under field conditions on their sensor equipment.

Chapter 10. Standards Development and Recommendations

The availability and accessibility of pavement condition and weather data influences maintenance operations decisions. A consistent way to convert numerical data into a well-defined description with standard terminology could improve maintenance communications between agencies, departments, and the public. Mobile road weather sensors provide useful information for transportation agencies, but standards and guidelines for interpreting data have yet to be established.

The project found that, for the most part, the accuracy of mobile pavement sensors does not meet the expectations of agencies that use the technologies. As the abilities of these sensors continues to improve and mature, manufacturers must utilize input and collaborate with agencies to best guide their research and development of future products.

10.1. Surface State

Descriptive road conditions are a key piece of information for drivers and agencies alike. To make safe, smart decisions, it is necessary to distinguish between types of surface states. Each of the four sensors tested in this project measures surface state, but they report these states using different terminology. The terms used to report surface state by each sensor are listed in Table 12. All devices use optical sensors to determine surface state, but the exact method differs between devices. Some devices also use other parameters, such as friction or water film height, to validate the optical readings. After speaking to Clear Roads members, most expressed that they felt each sensor measured too many surface states. When making decisions, the technical committee indicated that maintenance staff typically only distinguishes between Ice, Snow, Wet, or Dry.

Table 12. Surface State Conditions Measured by Each Sensor

Vaisala	High Sierra	Teconer	Lufft
Dry	Dry	Dry	Dry
Moist	Damp	Moist	Damp
Wet	Wet	Wet	Wet
Frosty	Freezing Wet	Slush, Ice or Snow with Water	Water + Ice
Snowy	Snow	Snow or Hoar Frost	Snow - Covered
Icy	Ice	Ice	Ice-Covered
Slushy	Slush		Snow-/Ice-Covered
			Chemically Wet

In addition to sensor vendors, other attempts have been made to define or summarize road conditions through a variety of means. Qualitative definitions, often using images or descriptive language, are common. Figure 43 provides an example from Bandara[8] to demonstrate terminology based on a visual reference.

Figure 43. Visual Winter Road Condition Determination Guide (Bandara, 2014)

Surface Condition	Description	Picture
Bare	Bare Pavement	
Centerline Bare (CL Bare)	Entire lane is cleared of snow, ice and slush.	
Wheel Track Bare (WT Bare)	Only wheel tracks are bare, snow/ice/slush in the other areas	
Loose Snow/Slush (Loose Snow)	Loose snow/slush covered	
Snow Covered (Snow)	Entire roadway is covered with packed snow and ice	

Using images from video footage taken during test runs for this project, a qualitative set of surface state definitions were created. Images were selected from time periods where sensors were in agreement about surface state type. Considering the differences in terms between each sensor and comments received from the Clear Roads committee, four surface states are recommended: Dry, Snow, Wet, and Ice. Each sensor reported additional surface states such as damp, moist, critically wet, etc. However, Clear Roads committee members identified that they prefer a short, basic list of

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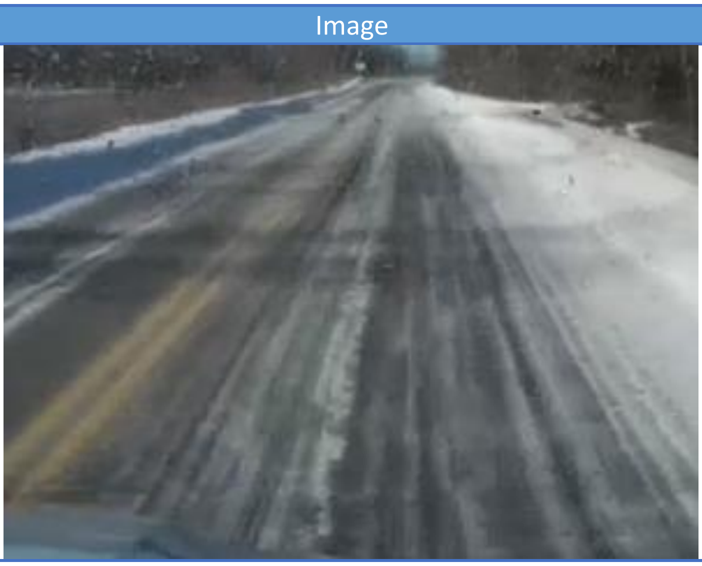
[8] Bandara, N. Pilot Study: Pavement Visual Condition and Friction as a Performance Measure for Winter Operations. 2014. http://docs.trb.org/prp/15-0574.pdf

surface states with clear definitions. This allows quick, easy, and simple translation of data for public consumption. These states and their definitions are presented in Table 13.

Table 13. Surface State Recommendations

Surface State	Definition	Image
Dry	Pavement has not been exposed to water for 24 hours. Pavement has been uncovered and allowed to air dry during the previous 24 hours.	
Snow	At least 5 mm of accumulated and unplowed snow.	
Wet	Pavement has a water film thickness of at least 0.5 mm.	

Surface State	Definition	Image
Ice	Frozen water with a film thickness of 0.5 mm or greater	

10.2. Grip Standards

Friction correlates to driving safety conditions such as wheel slip and stopping distance. The Idaho and Colorado State DOTs use several variables including road friction to calculate their version of a Weather Severity Index (WSI). Idaho uses a Vaisala DSC111 sensor for their friction readings, and classifies the friction intervals by mobility impact[9]:

Table 14. Idaho DOT Mobility Impact by Friction Interval

Friction Interval	Mobility Impact
0.6 and above	Normal Mobility
0.5 – 0.6	Slight Mobility Reduction
0.4 – 0.5	Moderate Mobility Reduction
0.3 – 0.4	Vehicles may start sliding off the road
0.3 and below	Multiple vehicle slide-offs possible; mobility greatly affected

Based on testing results from the project, the friction coefficient for even, dry, pavement is often given as 0.81 or 0.82. All four sensors studied use one of those values as the corresponding value as the maximum friction in their device user manuals. The devices report and utilize the friction coefficient differently. The Vaisala device gives a grip "warning" at friction values at or below 0.6 and a grip "alarm" at or below 0.4. These values can be manually changed at the user's discretion.

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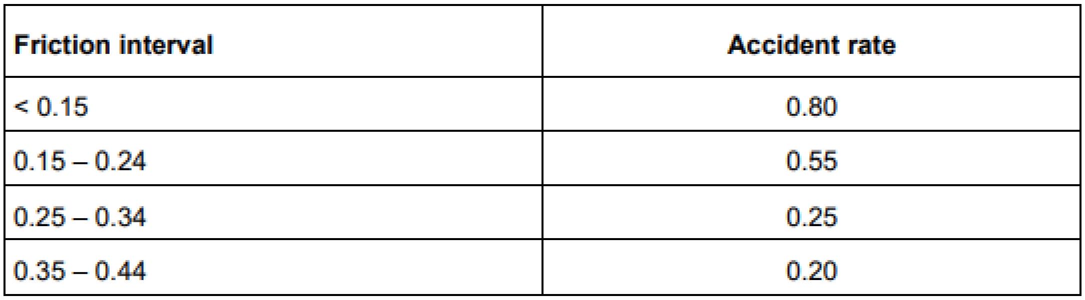
[9] ITS International. 2013. "Idaho Finds the Right Formula for Winter Maintenance."
http://www.itsinternational.com/categories/travel-information-weather/features/idaho-finds-the-right-formula-for-winter-maintenance/

The other sensors do not have set numerical values at which an alert or warning is given, though the High Sierra IceSight does report Good, Fair, or Poor grip depending on friction readings and other parameters.

Several studies have been conducted on modeling and classifying the relationship of friction on road safety. A Swedish 2001 review of friction and traffic safety by Wallman and Åström[10] categorizes friction readings by accident rate as shown in Table 15. The study measured surface friction and determined the accident rate of a small length of roadway.

Table 15. Accident Rate (Personal Injuries per Million Vehicle Km) by Friction Interval



Friction interval	Accident rate
< 0.15	0.80
0.15 – 0.24	0.55
0.25 – 0.34	0.25
0.35 – 0.44	0.20

Similarly, a regressive analysis performed on historical data in Germany produced the graph in Figure 44 of accident rates for various friction levels:

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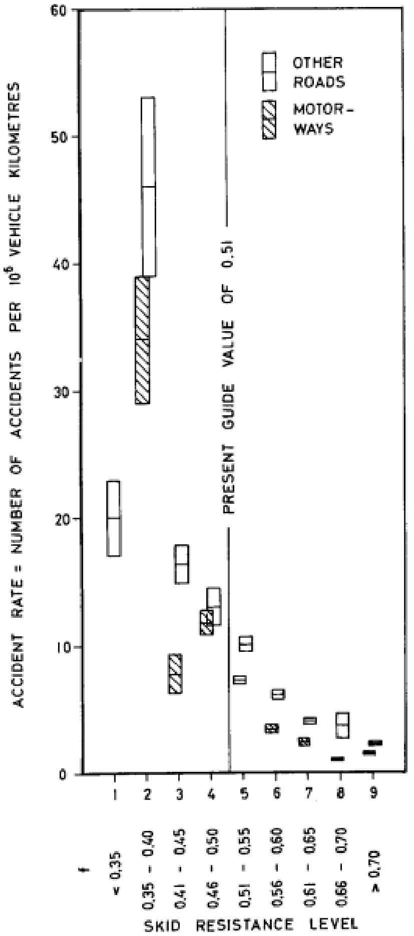
[10] Wallman, Carl-Gustaf and Henrik Astrom. 2001. “Friction Measurement Methods and the Correlation Between Road Friction and Traffic Safety: A Literature Review. *Swedish National Board and Transport Institute.* http://vti.diva-portal.org/smash/get/diva2:673366/FULLTEXT01.pdf

Figure 44. Accident Rate (Personal Injuries per Million Vehicle Km) by Friction Interval



Using a cumulative distribution function of the German study, it was found that approximately 50% of accidents on this roadway took place at friction levels of under 0.4, and around 92% of accidents took place at friction levels under 0.6.

Both Table 15 and Figure 44 show that decreasing friction results in an exponential increase of accident rates. However, because friction is unitless and varies depending on testing device, data will vary between studies. Additionally, many factors contribute to accident rates beside friction, such as location, pavement type, visibility, and lane widths.

During test runs conducted for this project, friction values would quickly rise and fall between high and low friction values for all sensors. Surface conditions rapidly shifted over just a short segment of roadway, making it difficult to assign a small range of friction for a section of pavement. Thus, while basic concepts of friction and grip can be applied generally to results, the current method of reporting friction makes treatment decision-making and standardization difficult.

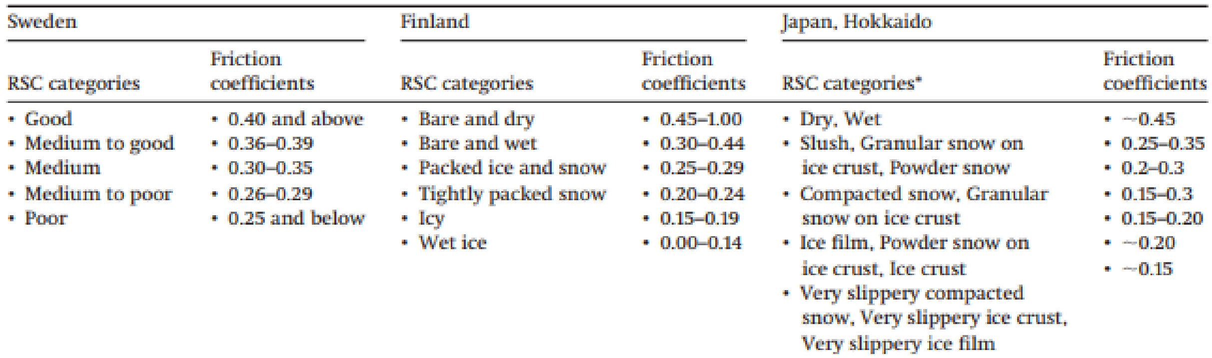
For winter maintenance agencies, friction reporting, like that shown in Table 15, would provide the most useful information for maintenance operations decision-making. Additionally, techniques to generalize friction values like those used by the Vaisala and High Sierra sensors are also acceptable. Reporting only numerical values at a high frequency makes it difficult for operators in the field to make real-time decisions. Generalized values are more practical for field use as they require little to no data interpretation for utilization.

10.3. Grip and Surface State Relationship

While surface state and grip are frequently measured against visual assessments and safety parameters, respectively, they also have been studied relative to one another.

Some agencies, such as the Finnish National Road Administration (Finland) and the Hokkaido Development Bureau (Japan), have adapted the approach shown in Figure 45.

Figure 45. Table from Fu et al., Road Surface Conditions and Friction Coefficients by Agency[11]



Sweden		Finland		Japan, Hokkaido	
RSC categories	Friction coefficients	RSC categories	Friction coefficients	RSC categories*	Friction coefficients
• Good • Medium to good • Medium • Medium to poor • Poor	• 0.40 and above • 0.36–0.39 • 0.30–0.35 • 0.26–0.29 • 0.25 and below	• Bare and dry • Bare and wet • Packed ice and snow • Tightly packed snow • Icy • Wet ice	• 0.45–1.00 • 0.30–0.44 • 0.25–0.29 • 0.20–0.24 • 0.15–0.19 • 0.00–0.14	• Dry, Wet • Slush, Granular snow on ice crust, Powder snow • Compacted snow, Granular snow on ice crust • Ice film, Powder snow on ice crust, Ice crust • Very slippery compacted snow, Very slippery ice crust, Very slippery ice film	• ~0.45 • 0.25–0.35 • 0.2–0.3 • 0.15–0.3 • 0.15–0.20 • ~0.20 • ~0.15

The reported conditions and corresponding friction values in Figure 45 are a good representation of systems used for agencies using friction as a means to define pavement conditions. Friction values may correspond to condition type, like in the case of Finland and Japan, or an assessment of overall condition quality, like Sweden. Grouping friction by condition type allows for a simple visual assessment of conditions. Grouping by road condition quality requires friction measurements but places the importance directly on impact to drivers. Since friction is unitless, results depend on the testing device and conditions, making it difficult to replicate results between various sensors.

The range of friction for a sensor's corresponding surface state as measured during the 26 test runs of this project are shown in Table 16. Not all surface states were encountered during test runs, and

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[11] Fu, Liping et al. 2016. "A risk-based approach to winter road surface condition classification" *NRC Research Press.* March 2016. http://web.a.ebscohost.com.ezp2.lib.umn.edu/ehost/pdfviewer/pdfviewer?vid=1&sid=da67800f-47b1-4d84-aeaa-62a38af3d8ea%40sessionmgr4010

therefore no data is included for those states. The High Sierra and Vaisala sensors have a wider range of friction detected for each state and rely on optical readings to make surface state determinations. The Lufft and Teconer sensors appear to have a more defined friction range for each surface state, similar to the approach shown in Figure 45 of Hokkaido, Japan. However, the variability and range of each sensor's friction reading is too high to effectively categorize surface state by friction.

Table 16. Surface State and Corresponding Friction Range

Vaisala		High Sierra		Teconer		Lufft	
State	Range	State	Range	State	Range	State	Range
Dry	.19-.82	Dry	.1-.82	Dry	.39-.81	Dry	.82-.82
Moist	.26-.82	Damp	.12-.82	Moist	.35-.81	Damp	.8-.82
Wet	.48-.82	Wet	.1-.82	Wet	.32-.75	Wet	.55-.8
Frosty	Not Measured	Freezing Wet	Not Measured	Slush, Ice or Snow with Water	.19-.72	Water + Ice	.7-.81
Snowy	.09-.77	Snow	.1-.82	Snow or Hoar Frost	.21-.58	Snow - Covered	Not Measured
Icy	.09-.71	Ice	.1-.78	Ice	.15-.81	Ice-Covered	.13-.81
Slushy	.44-.78	Slush	.12-.62			Snow-/Ice-Covered	.22-.55
						Chemically Wet	.77-.82

The range of friction values for a given surface condition is typically too wide to provide value for a winter maintenance decision process. Enabling meaningful use of mobile sensor data will require both a more consistent output of friction values for a given surface condition and standardizations of reported conditions across manufacturers.

10.4. Recommendations

To ensure clear communications with the public and cost-effective decisions about roadway treatment, a simple, definitive rubric is best suited for the needs of transportation agencies. While a generalized rubric may result in a loss of precision, it also allows for more practical use. Using the values from previous studies, suggestions from the Clear Roads committee, and testing results, a table was created as an example of such a rubric. The Clear Roads committee suggests that this type of approach be adopted by sensor manufacturers. The exact values of friction and verbiage may change based on findings of individual manufacturers but reported conditions would resemble those shown in Table 17.

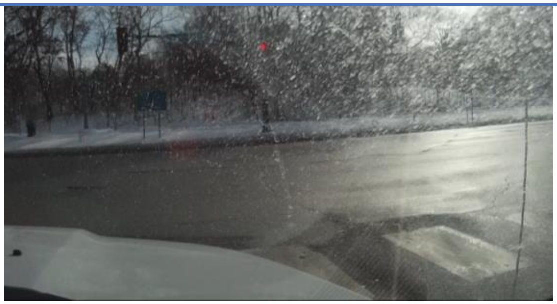
Table 17. Recommended Mobility, Surface State, and Friction Rubric

Road Surface Condition	Surface State	Friction Value
Poor	Ice	<0.2
	Snow	0.2-0.4
Medium	Wet	0.4-0.7
Good	Dry	>0.7

Table 18 combines the recommendations of Table 17 with additional definitions and imagery for the indicated surface states from Table 13.

Table 18. Recommended Rubric for Sensor Reporting

Road Surface Condition	Surface State	Definition	Image	Friction Value
Poor	Ice	Frozen water with a film thickness of 0.5 mm or greater		<0.2
	Snow	At least 5 mm of accumulated and unplowed snow.		0.2-0.6

Medium	Wet	Pavement has a water film thickness of at least 0.5 mm.		0.6-0.8
Good	Dry	Pavement has not been exposed to water for 24 hours. Pavement has been uncovered and allowed to air dry during the previous 24 hours.		>0.8

Chapter 11. Conclusion

Mobile Road Weather Information Sensors are an increasingly important part of winter maintenance operations for many states. Few comprehensive studies have been conducted comparing and evaluating sensors in field-case situations. Clear Roads commissioned this project to evaluate several different sensors so that transportation agencies could make informed purchasing and use decisions.

Four sensors were evaluated in this project: Lufft's MARWIS, Teconer's RCM411, High Sierra's Mobile IceSight, and Vaisala's DSP310. Throughout the study, sensors performed similarly in both qualitative and quantitative areas. No sensor was shown to be universally the best or worst across all parameters. Therefore, agencies interested in sensor performance should prioritize which factors are most important to their specific operational procedures.

11.1. Qualitative Parameters

11.1.1. Mounting

The four sensors evaluated had different recommended mounting locations, methods, and heights. High Sierra recommends mounting their IceSight sensor on the driver side rear window with a provided mounting bracket and has the largest range of acceptable mounting heights. Lufft recommends mounting their MARWIS sensor to the roof of the vehicle with suction cups and has the third-largest range of mounting heights. Teconer recommends mounting their RCM411 sensor at the trailer hitch with ball joint mounting equipment and has the smallest range for mounting height. Lastly, Vaisala also recommends mounting their DSP310 sensors to the roof with suction cups and has the second largest recommended range of mounting heights. Sensors were mounted to a secure wooden frame for this evaluation in order to best ensure simultaneous data collection from the same area of pavement. Sensors withstood the vibration and live-traffic testing very well with only the Teconer and Vaisala devices requiring additional mounting hardware after sensors came loose during early test runs. These mounting issues are not expected to be significant when used on vehicles. Sensors were mounted on adjustable cross-supports to evaluate sensor performance at varying mounting heights. It was observed that adjustments in mounting height did not affect overall data quality if sensors were recalibrated per the manufacturer's recommendations.

11.1.2. Connection and Communications

Lufft's MARWIS utilizes RS-485 or Bluetooth to collect data at intervals ranging from 0.1 to 5 seconds. The Teconer RCM411 communicates once every second to a Bluetooth unit, which then sends data from a cellular-connected Android device to a maintenance system server once every 15 seconds. The High Sierra Mobile IceSight communicates about once per second to a java-application running on a secondary device via RS-232, RS-485, and/or Wi-Fi communications. The Vaisala DSP310 connects to a mobile hotspot generated by a provided cell phone, and uses the phone's cellular network to transmit data once every 3 seconds. It sends the data to road weather management software or to other maintenance systems as needed. While all sensors had moments where they lost connectivity, the DSP310 frequently would disconnect, sometimes for minutes at a time, having a significant effect on data quality.

11.1.3. User Interface

Three of the sensors, the Vaisala DSP310, Lufft MARWIS, and Teconer RCM411, used mobile phone applications as their interface. The High Sierra IceSight connected to a Java application on a laptop computer. The Vaisala DSP310 had the most customizable interface, allowing for different parameters to be displayed as desired, but contains no graphic or map of the trip. The Teconer and Lufft were similar, with a set list of parameters' instantaneous values displayed. The Teconer included a graph displaying several values, whereas the Lufft showed a map color coded by surface state. The High Sierra interface consisted of a graph displaying data points in "balloons" representing surface state with technical information along the border of the graph.

11.1.4. Maintenance

Each manufacturer recommends similar maintenance procedures, such as periodic sensor inspection to ensure the lens is clean and reading values correctly. If the sensor is dirty, manufacturers suggest using a gentle, damp cloth with mild detergent to clean the lens. Vaisala and Lufft also suggest checking mounting, cables, screws, etc. regularly for looseness or damage. The Vaisala DSP310 requires a yearly filter change in the humidity probe and a yearly calibration of the probe at their labs. High Sierra suggests a calibration check annually.. High Sierra also offers an annual service plan option for an additional cost.

Testing took place from December 2017 to April 2018. During this period, no additional maintenance besides the recommended cleaning was performed. It is highly recommended that mounting is checked and secured frequently to ensure that sensors do not become detached from their mounts as a result of excessive vibration.

11.2. Quantitative Parameters

As with the qualitative parameters, sensors performed similarly during testing. Differences in the values come from differences in reporting ranges, sensor measurement area, and mounting. Changing device settings or positioning will alter sensor readout and performance to some degree and should be considered when reviewing this report. A table with test-result based rankings of these parameters is provided in Table 19.

11.2.1. Air Temperature Performance

All sensors performed similarly in measuring the ambient air temperature. Using the Omega OM-73 data taken in Phase I as a baseline, the Lufft sensor had the lowest average percent error. Sensor acclimation periods were also different enough to be considered as a factor for comparison. All sensors acclimated in less than 10 minutes.

11.2.2. Surface Temperature Performance

In Phase I tests, all four sensors had an average percent error of under 10%. The Lufft MARWIS sensor had the lowest overall average percent error, but the Vaisala DSP310 outperformed the Lufft sensor on aggregate and asphalt surfaces. In the Phase II tests, the High Sierra and Lufft sensors consistently reported temperatures 2-3 ⁰F above the Vaisala and Teconer sensors. Acclimation times were very short, with most sensors reporting the transition from warm, indoor surfaces to outdoor pavement immediately. The one exception was the Teconer sensor, which transitioned much more gradually to the outdoor pavement temperature.

11.2.3. Relative Humidity

Three sensors provide relative humidity values: High Sierra, Vaisala, and Lufft. Variability was observed between the sensors at times, but generally values were comparable. The Lufft sensor appeared to react more quickly to changes in humidity, which may account for some of the observed variation between sensors. The Lufft sensor also had the lowest percent error from the baseline values taken in Phase I. The Vaisala and High Sierra sensors generally agreed on trends in humidity change, with the Vaisala unit consistently producing values that were 2-4 percentage points higher than the other sensors.

11.2.4. Surface Condition

Surface condition reporting is difficult to quantify as the devices report a subjective description of "Wet", "Damp", "Dry", "Snowy", "Ice/Snow", etc. These terms are not rigorously defined and vary between manufacturer. A set of standard descriptive and qualitative terms is proposed in the standards/recommendations section of this report (see Table 18). Table 6 demonstrates that the values displayed are similar across the various sensors. The Vaisala DSP310 readings most frequently matched visual observations. It also appears all sensors display greater variability in reported condition when observing smooth asphalt than those over concrete surfaces.

11.2.5. Water Film Thickness

Three of the sensors report a water film thickness: Teconer, Vaisala, and Lufft. There was considerable variability in readings, and substantial differences between the reported values. The values did appear to correlate to each other, however, with changes of similar magnitude and direction occurring at the same time. The baseline measurement device selected for water film thickness did not prove to be an effective nor accurate tool to compare data against on rough and/or aggregate surfaces. When taking measurements on a smooth sheet of Plexiglas as a proxy for a road surface, Vaisala had the lowest percent error for water film, and Teconer the highest. However, both Teconer and Lufft greatly improved in accuracy as the water film thickness increased. As with other parameters, device-to-device comparisons were conducted and showed general similarity in the trend of values, even though the reported values themselves differ.

11.2.6. Friction

Friction is the most difficult parameter to evaluate as it is a unitless value with no established baseline. Friction is represented by a dimensionless scalar referred to as a “coefficient of friction” which varies for any given material with temperature, velocity, and the geometric properties of the surface. While certain devices attempt to measure the friction between an automotive tire and a road surface, none were available for this project. As a result, sensor outputs were compared to each other for this evaluation.

All sensors report friction as a number between 0 and 1. During a snow event test run, the High Sierra sensor reported the narrowest range of friction values (0.1 and 0.3) while the Vaisala sensor reported the greatest range (0.1 to 0.8). The sensors appeared to correlate with one another in terms of sensing changes in friction. As shown in Figure 41, there is a considerable, but not perfect, similarity between trends in friction values.

Overall, it appears that while sensors correctly sense changes in surface friction, the interpretation of that value must be determined individually for each manufacturer’s sensor. It also seems likely that very localized determinations of friction (over less than 100 meters, for example) may not be meaningful for material application or other maintenance activities. Given the distance covered by a moving vehicle in the 1-3 second sampling period of the sensor, the overall trend rather than the instantaneous value may be more informative.

11.3. Standards Development and Recommendations

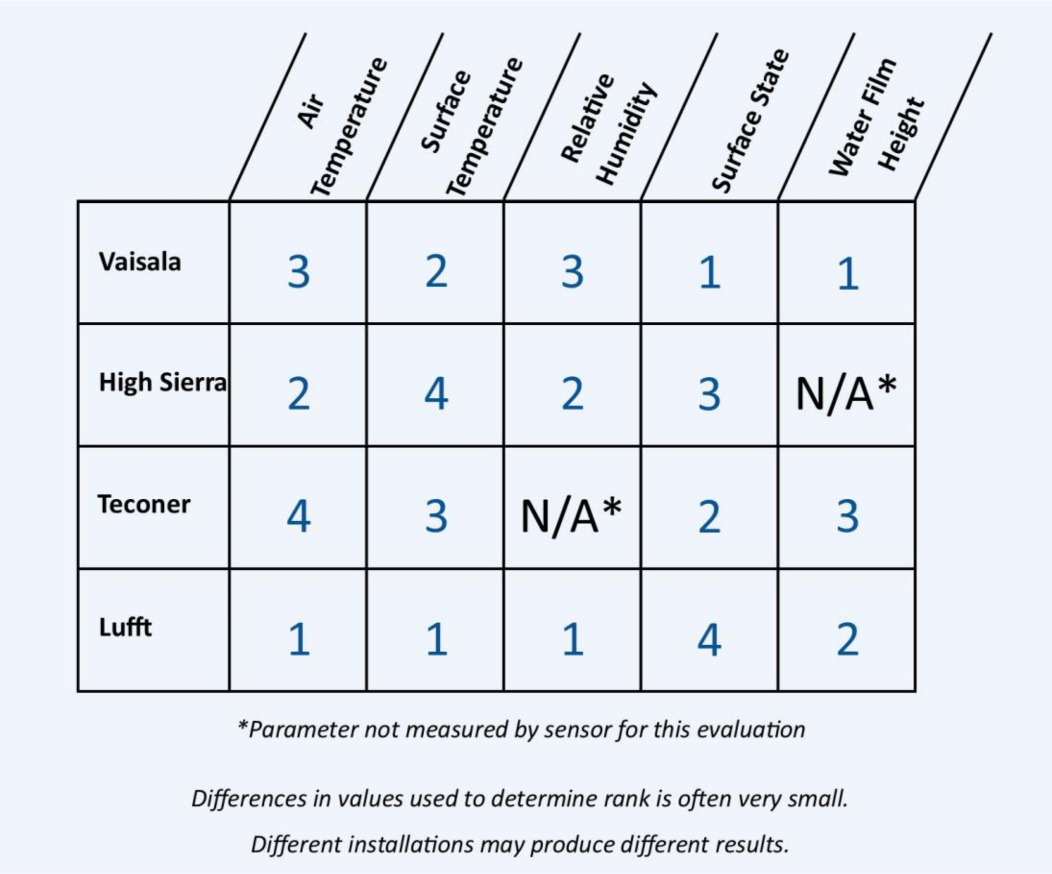
Differences across sensors and the high variability in their readings make establishing universal standards difficult. Combining feedback from Clear Roads members, test results, and previous research, this project developed standardized recommendations for future sensors. First, categorizing grip, surface state, and mobility impact into a few basic levels, as shown in Table 18, would provide agencies with information suited for everyday consumption. Categorization for friction, like that shown in Table 17, is recommended since specific values can be difficult to apply without additional qualifiers. Clear Roads members have posed the challenge to sensor vendors to improve the accuracy of air and pavement temperature, relative humidity, and water film height, especially in field applications rather than in lab evaluations.

11.4. Summary

In summary, sensors performed similarly across all parameters. Table 19 provides preliminary rankings of performance based on the results of Phases I and II. Air temperature, surface temperature, and relative humidity are ranked based on their percent error calculated in Phase I. Surface state is ranked by the tests in Phase I which determined how often sensor readings matched visual and physical observations. Friction ranking is not present as there was no baseline data source. If a sensor did not report a certain parameter, its ranking is noted with a "N/A."

It should be noted that sensors, in general, appear to perform similarly. The differences in values used to determine rank is often very small. Different installations may produce different results. The decision on which factors to consider when selecting a sensor for procurements should emphasize the parameters that each agency values the most. Other determining factors, such as cost, ease of installation, and parameters measured may be more significant in driving purchase decisions.

Table 19. Rank of Sensors by Quantitative Parameter



	Air Temperature	Surface Temperature	Relative Humidity	Surface State	Water Film Height
Vaisala	3	2	3	1	1
High Sierra	2	4	2	3	N/A*
Teconer	4	3	N/A*	2	3
Lufft	1	1	1	4	2

**Parameter not measured by sensor for this evaluation*

Differences in values used to determine rank is often very small.

Different installations may produce different results.

As further advancements are made in the industry, Clear Roads hopes that sensor accuracy will continue to improve, and devices will give clear information that will allow them to make timely decisions about winter maintenance. These improvements will help agencies provide better services and information to their communities and the public at large.

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