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Quantifying Salt Concentration on Pavement: Phase II

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Aurora Project 2014-02

Final Report
June 2018

About Aurora

Aurora is an international program of collaborative research, development, and deployment in the field of road and weather information systems (RWIS), serving the interests and needs of public agencies. The Aurora vision is to deploy RWIS to integrate state-of-the-art road and weather forecasting technologies with coordinated, multi-agency weather monitoring infrastructures. It is hoped this will facilitate advanced road condition and weather monitoring and forecasting capabilities for efficient highway maintenance and real-time information to travelers.

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16. Abstract

This report presents the laboratory findings from an evaluation of the Lufft MARWIS and the Teconer RCM411 sensors. The study focused on each sensor's ability to detect water film/ice depth (testing occurred at 28°F and -20°F), friction (testing occurred at 28°F), surface temperature (testing occurred at 28°F), and road condition/surface state (testing occurred at 28°F).

The objectives of this project were to evaluate the ability of the Lufft MARWIS and Teconer RCM411 sensors to perform in a typical winter maintenance environment, investigate the sensors' sensitivity to varying chloride concentrations, assess the repeatability of data and the sensors' mechanical reliability, and evaluate each sensor's state of development and cost to purchase, install, and maintain. The laboratory testing simulated real-world conditions of snow, ice, and/or slush on pavement, trafficking, and plowing and assessed how each sensor performed with the addition of each of these variables and detected the change in pavement condition/deicer performance throughout winter maintenance operations. The testing conditions were ideal in that they were consistent and reproducible.

For both sensors, the response time for data reporting was almost immediate (0 to 4 seconds), and the sensors detected greater water depth on the concrete samples than on the asphalt samples. Based on the performance of the road condition rating (MARWIS) and surface state rating (Teconer RCM411) features, it is safe to say that for both sensors this feature is a dynamic tool that can be used to determine the road condition remotely.

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QUANTIFYING SALT CONCENTRATION ON PAVEMENT: PHASE II – MARWIS AND TECONER LABORATORY SENSOR EVALUATION

Final Report
June 2018

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EXECUTIVE SUMMARY

The original goal of this project was to evaluate available mobile salinity sensors to determine their functionality in laboratory and field environments. Due to unforeseen circumstances (mainly the lack of reliable commercial salinity sensors), the project evolved to become an evaluation of mobile sensors used in winter roadway maintenance operations. The Lufft MARWIS and the Teconer RCM411 mobile sensors were used in the laboratory testing. Work in Phase I of this project identified these two sensors as being of interest to the project sponsor.

This report presents the laboratory findings from the evaluation of the Lufft MARWIS and the Teconer RCM411 sensors and focuses on each sensor's ability to detect the following:

- Water film/ice depth (testing occurred at 28°F and -20°F)
- Friction (testing occurred at 28°F)
- Surface temperature (testing occurred at 28°F)
- Road condition/Surface state (testing occurred at 28°F)

A summary of the findings is as follows:

- **Water/ice depth** – The Teconer RCM411 sensor detects the addition of liquid to the pavement surface with a fair amount of accuracy when water is first added. It also captures the phenomenon of the water freezing over time (i.e., the water depth decreasing). The sensor was not able to detect the first addition of water at very cold temperatures (-20°F) due to the rapid freezing of the water. The three sensing elements from the RCM411 sensor were capable of reliably detecting changes in pavement surface conditions under this investigated scenario. But, when water was detected by the RCM411 sensor, the data were highly variable due to the sensitivity of the sensor. The MARWIS sensor detected all applications of water regardless of air and pavement temperatures and appeared to be sensitive to detecting changes in the water/ice depth. Overall, the water/ice depth data reported by the MARWIS were very precise and tightly clustered (i.e., less variable), but it is not known if the data were more accurate. For both sensors, the response time for data reporting was almost immediate (0 to 4 seconds), and the sensors detected greater water depth on the concrete samples than on the asphalt samples.
- **Friction** – Friction data from both the Teconer RCM411 and MARWIS sensors were able to show accurately the changes in pavement friction over the course of laboratory testing. The common trend in friction values throughout testing was that friction started high and remained high following application of the anti-icer, but friction values then declined to unsafe (slippery) conditions following the application of snow and subsequent compaction and trafficking. Once the snow was plowed/scraped off the pavement surface, the friction values increased to moderate levels to create safer pavement conditions.
- Changes in friction were reported by the sensors almost instantaneously (within seconds, as each new data point was recorded), but it took upwards of 70 seconds for the data to stabilize during testing. This does not appear to be a fault or error in the data. Instead, the sensors appeared to be observing the change in friction as the pavement condition changed, with the variability due to the sensitivity of the sensors.

- **Pavement Surface Temperature** – The Teconer RCM411 recorded pavement surface temperature within 1 degree of the room temperature before snow was added to the pavement surface. Once snow was added, through compaction and trafficking, the pavement temperature was significantly colder by 1°F to 2°F, with the pavement temperature warming back to the room temperature once the snow was plowed/scraped off. In contrast, the pavement surface temperature data from the MARWIS was not accurate, recording temperatures 10°F to 15°F colder than the room temperature. Efforts were made to work with Lufft to obtain more accurate pavement surface temperature data, but the issue was not resolved prior to the end of testing. Interestingly, the MARWIS pavement temperature data appeared to be the only data that were "off," suggesting that maybe this sensor element needed to be replaced.
- **Road Condition and Surface State** – Based on the performance of the road condition rating (MARWIS) and surface state rating (Teconer RCM411) features, it is safe to say that for both sensors this represents a dynamic tool that can be used to determine the road condition remotely. For both sensors, the derived road condition and surface state rating by MARWIS and the RCM411, respectively, were more variable when collected from asphalt pavement than from concrete.
- **Ice Percent** (MARWIS only) – The data from the snow and trafficking testing showed that the ice percent data from the MARWIS sensor were fairly consistent. The only data variability occurred when the sensors detected the anti-icer frozen as ice on the pavement surface and when the snow was plowed/scraped off the pavement sample, likely creating a more variable surface condition.
- **Chloride concentration in the plowed snow** – Under the investigated scenarios, the asphalt samples showed higher concentrations of chloride in the plowed-off snow and, therefore, lower concentrations of chlorides remained on the pavement surface. In comparison, the concrete samples had much lower chloride concentrations in the plowed-off snow, and much higher chloride concentrations remained on the pavement surface. Another interesting pattern revealed by the testing was the variation in the percentage of residual chloride remaining on the pavement surface with changes in temperature. When pavement type was not considered, more residual chloride appeared to be present at warmer temperatures and less residual chloride was present at colder temperatures. This observation warrants additional testing to determine if this pattern is in fact a statistically valid trend.

At first glance, the results of this effort may be a comparison between the MARWIS and Teconer RCM411 sensors. The reality is that this research evaluated the performance of each sensor as a standalone unit under a controlled laboratory simulation of the field environment. It is important to note that the testing conditions were ideal in that they were consistent and reproducible. But, from a field use perspective, the air and pavement temperatures reflected relatively "warm" winter conditions (28°F) for the bulk of the testing, and the sensors were not being exposed to a harsh field environment with splash, spray, and debris from the road impacting the sensors and the readings. There were some issues with the sensors at the colder -20°F testing temperature. Additional issues with equipment not functioning at the cold temperature precluded snow and trafficking testing at -20°F. Because the majority of testing was conducted at the warmer 28°F, the conclusions from this effort should be applied with caution. Given the conservative, mild nature of the testing, it is likely other issues or sensor values that could occur in the field were not observed in the laboratory.

For example, one issue for which the research effort cannot provide input is the frequency and methods for cleaning the sensors to ensure quality data collection. A number of deviations and issues were encountered in the laboratory testing and are discussed as follows.

At temperatures below 5°F, MARWIS needed a 15-volt power supply, because the 12-volt supply provided was not sufficient. Additionally, the MARWIS provided communications within a minute, but a status light provided a cold-temperature warning for several minutes during a "warm up" period before indicating it was ready. The duration of the "warm up" period for MARWIS varied with the temperature; at 25°F, warm up time was about 10 minutes, but at -20°F, warm up took 60 to 90 minutes. If the sensors were mounted on vehicles stored in garages, the warm-up period would conceivably be shorter.

With MARWIS, when calibration was conducted on concrete pavement, it would accurately report dry pavement conditions for concrete, then asphalt, then concrete when swapping the pavement samples. However, when it was calibrated on asphalt pavement, it would often inaccurately report concrete pavement as "chemically wet" when it should have shown "dry." In comparison, the RCM411 more accurately reported dry pavement regardless of whether calibration occurred on asphalt or concrete samples, except during longer breaks between tests.

An interesting result found by both sensors was the increased variability of reported data from asphalt versus concrete pavement samples. Due to the consistency in increased variability of data from both sensors and the identified need for calibration on each pavement type, which was conducted prior to each test, the researchers feel the increased variability of data from asphalt pavement is not an error in the data being reported but instead may be an artifact of the data being collected from asphalt pavement. Additional research is recommended to determine if readings from all asphalt pavements are as variable as the data collected in this research effort. Likewise, it should be further considered whether readings from all concrete pavements are as consistent as the data collected by both sensors in this research effort.

INTRODUCTION/BACKGROUND

The original goal of this project was to evaluate available mobile salinity sensors to determine functionality in the laboratory and field environments. Due to unforeseen circumstances, the project evolved to become an evaluation of mobile sensors used in maintenance operations on winter roadways. The Lufft Mobile Advanced Road Weather Information Sensor (MARWIS-UMB) and the Teconer RCM411 mobile sensors were used in the laboratory testing. Work in Phase I of this project identified these two sensors as being of interest to the project sponsor.

This report presents the laboratory findings from the evaluation of the Lufft MARWIS and the Teconer RCM411 sensors and specifically focuses on each sensor's ability to detect the following:

- Water film/ice depth
- Friction
- Surface temperature
- Road condition/Surface state

The objectives of this project were as follows:

- Evaluate the ability of the Lufft MARWIS and Teconer RCM411 sensors to perform in a typical winter maintenance environment
- Investigate the sensors' sensitivity to varying chloride concentrations
- Assess the repeatability of data, the sensors' mechanical reliability, and each sensor's state of development and cost to purchase, install, and maintain

The objectives for the laboratory testing were as follows:

- Simulate real-world conditions of snow, ice, and/or slush on pavement, trafficking, and plowing
- Assess how each sensor performed with the addition of each of these variables and detected the change in pavement condition/deicer performance throughout winter maintenance operations

Background

Lufft MARWIS

The Lufft MARWIS-UMB mobile sensor measures road surface temperature, water film height, dew point temperature, road conditions (including dry, moist, wet, chemically wet, snow, or ice), ice percentage, friction, and relative humidity above the road surface. Currently, the MARWIS system does not provide data on the salt concentration present on the pavement surface. At this time, the MARWIS system reports the road surface as chemically wet if it senses moisture and the road temperature is below 32°F. Lufft is working to modify this reading to report salt concentration on the pavement surface.

The MARWIS sensor uses optical (infrared) spectroscopy measurements. The four emitting and two receiving diodes capture the reflecting behavior of the road surface at varying wavelengths (Lufft n.d.) (Figure 1).

Lufft n.d., © MARWIS 2015

Figure 1. MARWIS-UMB components

The different spectral properties of substances on the road such as water, ice, etc., can be determined from the captured values. Road surface temperature is measured using a non-invasive pyrometer that reports relative humidity. Water film height is measured with a non-invasive optical spectroscopy sensor (emitting and receiving diodes). Ice percentage is determined from optical spectroscopy (emitting and receiving diodes), where the frozen part of the aqueous solution on the road surface is determined and percent is calculated. Road condition is gauged by using the measured water film height, road surface temperature, and ice percentage values. From these variables, the sensor determines if the road is dry, damp, wet, snow/ice, or chemically wet.

The Lufft MARWIS sensors are mounted on trucks or cars using a rack or magnet with two measuring height options (1 or 2 meters [3.2 or 6.5 ft]) between the sensor and the road. The sensor has a protective cover. The information is displayed in the vehicle on an iPad mini (or iPhone) using the MARWIS app (available for Android OS as well), which shows the information in various formats based on the tab selected. The information is sent using Bluetooth technology and does not require the vehicle to have a global positioning system (GPS) onboard. The Glance software can show a map with road conditions, which can be color-coded to show ice, dry pavement, rain, etc. Air and pavement surface temperatures and water height are also shown. An alert system can be set up for specific parameters based on the user's needs. Data from multiple sensors can be viewed on one screen (with up to six unique profiles per iPad), or separate screens. Historical data also can be viewed. The MARWIS system has a list price of $5,300 (2015 US dollars). Lufft offers a free three-month trial.

Figure 2 shows the MARWIS sensor mounted on a vehicle.

Lufft 2014

Figure 2. MARWIS sensor without protective cover and mounted on a truck

The MARWIS-UMB system is unique in that it can automatically align the recording of pavement surface structures, including pervious pavement, mastic asphalt, and low-noise or concrete surfaces with the collected data. Some key features of the Lufft MARWIS-UMB are shown in Table 1.

Table 1. Key features of Lufft-ARS31Pro-UMB

Size	Dimensions	Height - 110 mm, Width - 200 mm, Diameter - 100 mm
	Weight	1.7 kg
Storage conditions	Permissible ambient temp.	-40 to 70 °C (-40 to 158 °F)
	Permissible relative humidity	<95% relative humidity, non-condensing
Operating conditions	Operating voltage	10 to 28 VDC, approx. 3VA
	Permissible operating temp.	-40 to 60 °C (-40 to 140 °F)
Dew point temperature	Measuring range	-50 to 60 °C (-58 to 140 °F)
	Accuracy	± 1.5 °C (from 0 to 35 °C)
Water film height	Measuring range	0 to 6000µm
	Resolution	0.1µm
Road surface temperature	Principle	Pyrometer (non-contact infrared thermometer)
	Measuring range	-40 to 70 °C (-40 to 158 °F)
	Accuracy	± 0.8 °C at 0 °C
	Resolution	0.1 °C
Rel. humidity above road surface	Measuring range	0 to 100% rel. humidity
Friction	Measuring range	0 to 1 (smooth to dry)
Road condition	Dry, moist, wet, ice, snow/ice, critical/chemical wet	

The MARWIS system is commercially available and being field tested in many states and countries, but at this time does not report salinity values. The conversion of the chemically wet parameter to report salinity or product concentration on the pavement surface is still under development.

Teconer RCM 411

The Teconer RCM411, or Road Condition Monitor, provides real-time information on road surface conditions such as dry, moist, wet, slushy, snowy, or icy road surfaces (which are color-coded in the user interface), water thickness, and coefficient of friction (www.teconer.fi/en/winter.html) (Figure 3).

Figure 3. Teconer RCM411 mounted on the rear bumper of passenger vehicle

The RCM411 is an optical remote sensor based on spectral analysis that measures the optical reflection signals from the road surface. The system then analyzes the data to produce a road surface condition and friction report. A new RCM411 costs around $9,000 (2015 US dollars). Currently, Teconer is developing a method to use friction data and pavement temperature to calculate the brine fraction (or salt concentration) on the road surface (Haavasoja 2015), but at present this only works for sodium chloride (NaCl) based products. This sensor does not directly measure salinity on the road surface. While the feature is still under development and not commercially available, the developers are very willing to make it available for research and field testing (Personal communication, T. Haavasoja, March 2015). Teconer is unsure if this will turn out to be a revised version of the RCM411 or a separate technology altogether.

Issues associated with the brine fraction (salt concentration) method occur at warmer temperatures (e.g., well above freezing) and when friction values are not changing, such that the calculation method does not work. In most instances, this method will not work when the road surface is dry, because friction values will not be changing. Teconer reports an error rate of about 3% for NaCl when calculating the brine fraction. The current RCM411 system is being tested in refreeze studies and is being used for quality control. A summary of working parameters and functional capabilities of the RCM411 sensor appears in Table 2.

Table 2. Summary of working parameters and functional capabilities of the RCM411

Size	Dimensions	Length - 100 mm, Diameter - 75 mm
	Weight	750 g
Storage conditions	Permissible ambient temp.	-40 to 70 °C (-40 to 158 °F)
	Permissible relative humidity	<95% relative humidity, non-condensing
Operating conditions	Operating voltage	9 to 30 VDC, power consumption 10 W
	Permissible operating temp.	-20 to 50 °C (-4 to 122 °F)
Water film height	Resolution of thickness	0.1 mm
	Detection limit	0.03 mm
	Accuracy of thickness	0.1 to 1.0 mm (10% above 1.0 mm)
Friction	Resolution	0.01

The RCM411 is usually mounted to the ball hitch of a vehicle with a preferred measurement height of 22 inches. The RCM411 uses Bluetooth technology to communicate to phones or tablets with mobile apps available for Apple and Android OS.

The RCM411 has two methods for measuring friction. One is based on the optical measurements, which was the only method used in the laboratory testing portion of this project. The second method (the braking friction feature) of the RCM411 can be enabled if the phone or tablet is mounted/fixed inside the vehicle.

METHODOLOGY

All laboratory tests were conducted in the Subzero Science and Engineering Research Facility (Subzero Lab) at Montana State University in Bozeman. The laboratories have sophisticated temperature controls to within 1°C and equipment to make snow to provide consistent testing conditions. Tests were conducted at temperatures of 28°F and -20°F. These temperatures were chosen for testing because (1) the NaCl-based deicer functions well above 15°F and (2) the project was tasked with learning how the sensors perform in very cold conditions.

Pavement Samples

Traditional asphalt and unreinforced concrete pavements of 9 in. width, 20 in. length, and 1 in. thickness were used (Figure 4 and Figure 5). Pavement samples were soaked, scrubbed, rinsed, air dried, and then equilibrated to the testing temperature for at least 18 hours between each test.

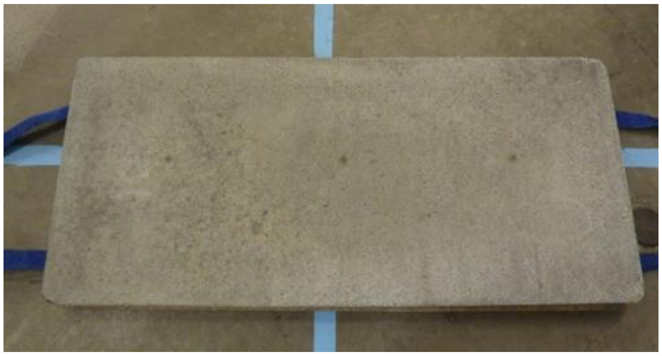


Figure 4. Unreinforced concrete pavement specimen

Figure 5. Asphalt pavement specimen

Sensor Mounting, Power, and Communications

MARWIS and RCM411 are intended to be vehicle-mounted mobile sensors with specific mounting hardware and specifications. In the laboratory, sensors were mounted in fixed positions within the manufacturer-specified tolerance levels for height and angle. The RCM411 was clamped to a table (Figure 6 and Figure 7) and MARWIS was suspended from a tripod (Figure 8 and Figure 9). The mounting heights and angles used during testing for each sensor are shown in Figures 8 and 9. The sensor vendors report a range for mounting height and angle that can be used.

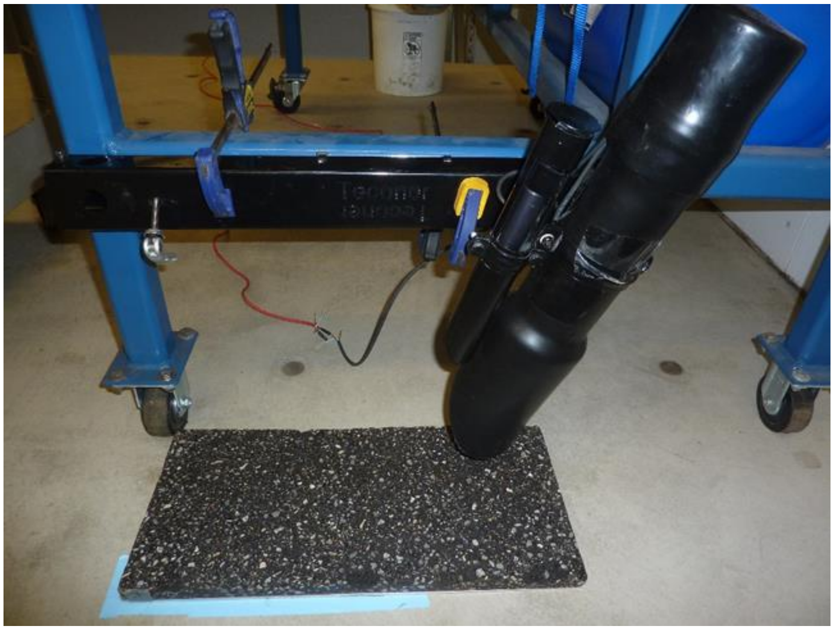


Figure 6. RCM411 stationary mount in the Subzero Lab

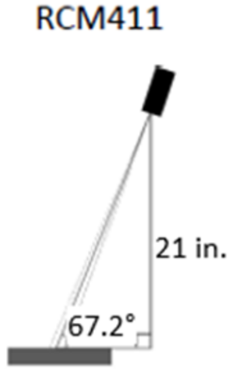


Figure 7. Recommended mounting height and angle for the Teconer RCM411

Figure 8. Recommended mounting height and angle for the MARWIS

Figure 9. MARWIS suspended from a tripod

Each sensor used a separate DC power supply capable of supplying the required voltage and amperage. In general, 12 volts was sufficient for both the MARWIS and RCM411, except that at temperatures below 5°F, MARWIS needed a 15-volt power supply. The sensors were fixed and subject to sustained freezing conditions in the laboratory. After powering on the sensors, RCM411 communications and data were ready for calibration within minutes. MARWIS provided communications within a minute, but a status light provided a cold-temperature warning for several minutes during a "warm up" period before indicating it was ready. The duration of the "warm up" period for MARWIS varied with the temperature: at 25°F, warm up was about 10 minutes, but at -20°F, warm took about 60 to 90 minutes. If the sensors were mounted on vehicles stored in garages, the warm-up period would conceivably be shorter.

Manufacturer-supplied devices and apps—Android OS phone for RCM411 and iPad for MARWIS—provided communications for each sensor. Bluetooth communication between the sensor and smartphone/iPad was easy to set up and user friendly. The maximum distance between the sensor and smartphone/iPad was about 20 feet during testing and worked well at this distance. The apps provided real-time data in graphical and tabular format with updates every 1 to 2 seconds.

Spreadsheets with data at 1-second intervals were provided by manufacturer-maintained websites (Lufft with user/password-controlled access and Teconer on a webpage for all devices that communicate with their servers).

Preliminary Testing – Calibration

The app can be used to calibrate the MARWIS and RCM411 while the sensors are stationary and pointing to dry pavement. There are several user-specified options, the most significant of which is the option to choose asphalt or concrete pavement type. With MARWIS, when calibration was conducted on concrete pavement it would accurately report dry pavement conditions for concrete, then asphalt, then concrete when swapping the pavement samples. However, when it was calibrated on asphalt pavement, it would often inaccurately report concrete pavement as "chemically wet" when it should have shown "dry."

RCM411 was more accurately able to report dry pavement regardless of whether calibration occurred on asphalt or concrete samples, except during longer breaks between tests. For this reason, at the beginning of each experiment, the sensors were calibrated with each pavement specimen used for the test.

Preliminary Testing – Salt Application Methods

Three salt application methods were tested, and their advantages and disadvantages were noted. The methods tested were as follows:

1. Paint sprayer mounted to a track and equipped with fine spray mist nozzles – This method provides very fine, uniform droplets, but the significant overspray makes it difficult to measure exactly how much salt was applied on the pavement sample. This method and the equipment have been used successfully in these lab facilities as reported in Akin et al. (2017).
2. Pipette application of deicers – Larger, discrete droplets are applied to the pavement surface in a uniform pattern. This treatment does not provide consistent and uniform coverage of deicer on the pavement surface. This presents a problem given the small location measured by the MARWIS and Teconer RCM411 sensors on the pavement surface. This method significantly increases data variability. Attempts were made to spread out the drops after pipetting, but this only worked on concrete, not on asphalt. This method and the equipment have been used successfully in these lab facilities as reported in Muthumani et al. (2015).

3. Spray bottle – This method provides a range of droplet sizes, and both the stream and spray features were tested. While the spray bottle application of deicer was not as uniform as the paint sprayer, it was easier to measure the exact quantity of deicer applied. The spray bottle was weighed before and after spraying to measure exactly how much liquid was applied on the pavement. An Excel calculator was developed for this application method to allow for easy calculation of target application rates. The actual applied application rate was calculated based on the changes in mass of the squirt bottle. A disadvantage of this method was that the minimum possible application rate was about 40 gal/l-m. For this reason, no tests were conducted with application rates less than 40 gal/l-m.

Lab and Sample Preparation

For each round of testing, the environmental chamber temperature was adjusted and allowed 24 hours to equilibrate. At this time, each pavement sample was cleaned to ensure that no residual deicing product remained on the pavement surface. After drying, the pavement samples were placed in the environmental chamber to equilibrate. For this reason, the room/air temperature should be the same as the pavement temperature. Once the pavement sample had equilibrated to the room temperature, the sensors were turned on, “warmed up,” and calibrated for each pavement type.

Two types of tests were conducted: measurement of (1) water depth/ice depth on the pavement samples and (2) trafficked snow on pavement. For the “water depth/ice depth” tests, a pavement specimen was placed under a sensor (MARWIS or RCM411), and the specimen remained stationary for the duration of the test as layers of water were applied to the pavement and allowed to freeze. In “trafficked snow on pavement” tests, the pavement sample was moved for deicer application, then shifted to the compactor, followed by the trafficking and scraping of snow. Between each of these actions, the samples were placed under the MARWIS and RCM411 to collect data. More detailed methodology for each of these types of tests is presented next.

Water Depth/Ice Depth Test

Water depth/ice depth tests were conducted at 28°F and -20°F. Pavement samples had a silicon dam created around the edge of a 7 in. square area to hold in all liquids, and a series of tests were conducted to investigate how the depth of liquid influenced the sensor readings (Figure 10).

Figure 10. Asphalt and concrete samples with the 7 by 7 in. silicon dam for water depth/ice depth measurements

Once a pavement sample was placed under a sensor (MARWIS or RCM411), it remained in place for the duration of the test. These steps were followed for the water depth/ice depth tests:

1. Placed clean and equilibrated pavement sample under sensor where it remained throughout testing.
2. Calibrated sensor (MARWIS or RCM411).
3. Applied salt brine with spray bottle and calculated actual application rate by measuring mass dispensed from bottle and the area (length and width) on which salt brine (NaCl) was sprayed. The nozzle of the squirt bottle was set to a medium-fine spray. The squirt bottle was squeezed two to three times at less-than-full range.
4. First water application—target depth of 0.5 mm. Poured about 16 ml of distilled water from a graduated cylinder, then the water was spread with a plastic non-absorbent spreader. The water was applied approximately 13 minutes after the salt brine was applied to the sample. The mass of water added was measured, and the depth of standing water was calculated based on the volume of water divided by the area (49 $in.^2$). For tests conducted at 28°F, the added water was easy to spread evenly across the 7 in. square area. When testing at -20°F, the water froze quickly, and the water depth was more variable (probably up to 0.7 mm depth in spots).
5. Waited for water to freeze and MARWIS or RCM411 readings to show sample is no longer changing (about 45 minutes at 28°F and about 10 minutes at -20°F).
6. Second water application (target 0.5 mm)—total depth 1 mm. Once again, about 16 ml of distilled water was applied to the frozen first layer of ice and then spread with a plastic non-absorbent spreader. The mass of water was added and the depth measured.
7. Waited for water to freeze and MARWIS or RCM411 readings to show the sample was no longer changing.
8. Third water application (target 1.0mm)—total depth 2 mm. About 32 ml of water was applied, the mass was measured, and depth was calculated.
9. Waited for water to freeze and MARWIS or RCM411 readings to show sample was no longer changing.

10. Fourth water application (target 1.0mm)—total depth 3 mm. The mass was measured and depth calculated.
11. Waited for the water to freeze and MARWIS or RCM411 readings to show sample was no longer changing.
12. End test.

Note that the MARWIS and Teconer RCM411 sensors report water freezing into ice in different ways. MARWIS reports ice fraction. On the first water/ice layer, the ice fraction reading would increase from 0 to 100%. For the second, third, and fourth layers, the ice fraction would drop to about 60% and then increase as the upper layer froze. For the third and fourth layers, sometimes the ice fraction would not reach 100% even after it was completely frozen. MARWIS also reports surface state, which would change from wet to ice during the testing process. The Teconer RCM411 reports surface state and it would go from wet to slush to ice during the testing process.

Ten water depth/ice depth tests were conducted using the MARWIS or RCM411 sensors, concrete or asphalt pavement, and temperatures of either 28°F or -20°F. The sensor, pavement type, and actual salt brine application rates and water depths for each test are shown in Table 3.

Table 3. Completed water-ice depth testing parameters, and sensor and pavement types

Temp (°F)	Sensor (M-MARWIS or T-Teconer)	Pavement Type (C=concrete or A=asphalt)	Salt Brine app rate (gal/LM)	1st Water app depth (mm)	2nd Water app depth (mm)	3rd Water app depth (mm)	4th Water app depth (mm)
28	M	C	53.2	0.51	0.52	1.01	1.03
28	M	A	33.9	0.52	0.52	1.02	1.00
28	T	C	84.5	0.52	0.51	1.03	1.01
28	T	A	182.9	0.54	0.50	1.01	1.01
-20	M	C	60.9	0.53	0.51	0.99	0.97
-20	M	C	43.8	0.51	0.52	0.98	0.96
-20	M	A	54.4	0.56	0.53	1.03	1.04
-20	T	C	50.5	0.53	0.51	1.06	0.98
-20	T	A	86.8	0.51	0.51	0.98	0.96
-20	T	A	53.0	0.51	0.51	0.98	0.98

Trafficked Snow on Pavement Test

The objective of the trafficked snow on pavement tests was to create more realistic winter conditions using snow, trafficking, and scraping (i.e., plowing) while collecting MARWIS and RCM411 sensor data to capture the changes measured by each sensor with each changing condition throughout the experiment. A pavement sample (asphalt or concrete) was centered under the MARWIS or RCM411 sensor and moved back and forth 10 times for approximately 3 minutes to collect the data. These steps were followed for the trafficked snow on pavement tests:

1. The pavement sample was placed under the MARWIS and calibrated.
2. The pavement sample was placed under the RCM411 and calibrated.
3. The sample was then placed under the MARWIS, and salt brine was sprayed using the same methods described previously (Figure 11). The mass of the applied salt brine and application area was measured to calculate the application rate. About three to four full squirts were required to cover the sample (9 in. by 20 in.) with salt brine without over-spraying.

Figure 11. Asphalt sample with salt brine applied

4. The sample was moved back and forth under MARWIS for 3 minutes.
5. The sample was then placed under RCM411 and moved back and forth for 3 minutes.
6. The sample was placed in a compactor and 800 g of snow was sieved through a 1 mm sieve onto the sample surface. The sieve was removed, and the snow was spread evenly across sample surface, with a loose depth of approximately ¾ in. of snow (Figure 12).

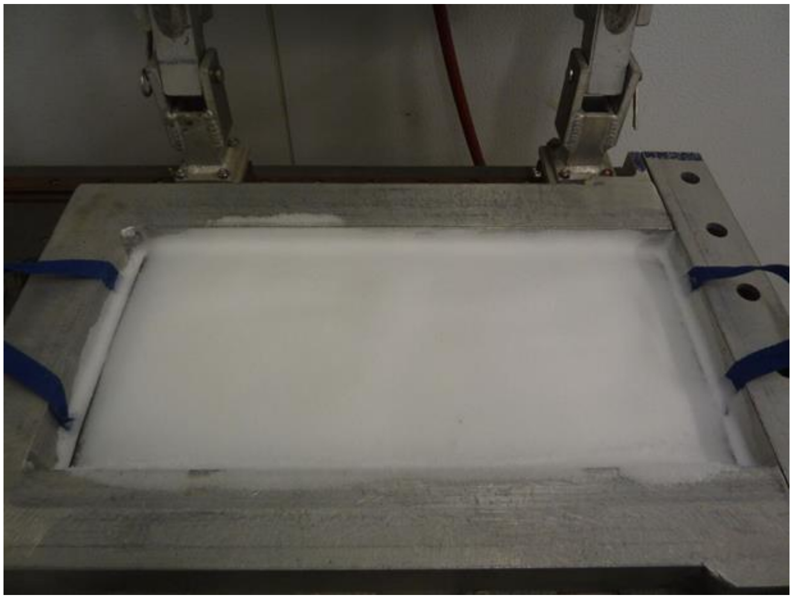


Figure 12. Pavement sample with compacted snow in the compaction machine

7. The snow was compacted at 60 psi for 5 minutes. The compactor, an aluminum box with a rubber membrane in the lid, was filled with compressed air to compact the snow with uniform pressure.
8. The sample was then placed under the MARWIS and moved back and forth for 3 minutes.
9. The sample was then placed under the RCM411 and moved back and forth for 3 minutes.
10. The sample was placed in a trafficking device and trafficked for 500 passes (about 20 minutes) with a load of 630 lbs on the tire (Figure 13).

Figure 13. Trafficking of snow on an asphalt pavement sample

11. The sample was then placed under the MARWIS and moved back and forth for 3 minutes.

12. The sample was then placed under the RCM411 and moved back and forth for 3 minutes.
13. The snow was then scraped (or plowed) from the pavement sample (Figure 14 and Figure 15). The scraped portion of snow was collected and tested for chloride concentration.

Figure 14. Trafficked snow scraped off the asphalt pavement sample

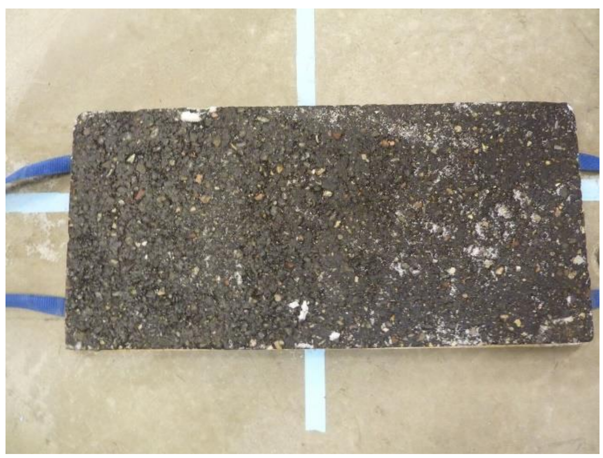


Figure 15. Asphalt pavement sample after trafficked snow has been fully scraped off

14. The sample was then placed under the MARWIS and moved back and forth for 3 minutes.
15. The sample was then placed under the RCM411 and moved back and forth for 3 minutes.

Similar methods for snow making, snow application, compaction, tracking, and plowing have been used in peer-reviewed research projects by Muthumani et al. (2015) and Akin et al. (2017).

Six trafficked-snow-on-pavement tests were conducted at 28°F, three with concrete pavement and three with asphalt pavement, as shown in Table 4. The trafficking machine stopped working, with additional attempts at -20, 0, and 5°F, which provided no further usable data.

Table 4. Completed trafficked-snow-on-pavement tests

Date of testing	Anti-icing application rate (NaCl, liquid) (mg/L)	Concrete/Asphalt (C/A)
7/3	41.36	C
7/3	59.4	A
7/5	47.8	A
7/18	55.7	C
7/27	27.9	C
7/31	36.1	A

Note: All testing was done at 28°F and data was collected from both MARWIS and Teconer RCM411 sensors

The trafficked snow that was scraped from the pavement sample was collected and stored in labeled plastic bags in the cold lab to keep it frozen. The snow was then tested for chloride concentration to aid in the calculation of how much residual chloride remained on the pavement sample following trafficking and scraping versus how much was removed with the snow. Melted snow samples were hand-delivered to Bridger Analytical Lab, Inc. (Bozeman, MT), where chloride concentration was measured.

RESULTS

Water/Ice Depth Measurements

The Teconer RCM411 and Lufft MARWIS sensors report water and water/ice depth, respectively, on the pavement surface. The goals of the laboratory testing were to ascertain how well each sensor reported water/ice depth versus what water was applied and report on data reporting lag times and observed trends in the testing. Table 5 summarizes the experimental conditions for the water/ice depth testing.

Table 5. Testing parameters and measured water height

Temp (°F)	Sensor (M-MARWIS or T-Teconer)	Pavement Type (C=concrete or A=asphalt)	Salt Brine app rate (gal/LM)	1st Water app depth (mm)	2nd Water app depth (mm)	3rd Water app depth (mm)	4th Water app depth (mm)
28	M	C	53.2	0.51	0.52	1.01	1.03
28	M	A	33.9	0.52	0.52	1.02	1.00
28	T	C	84.5	0.52	0.51	1.03	1.01
28	T	A	182.9	0.54	0.50	1.01	1.01
-20	M	C	60.9	0.53	0.51	0.99	0.97
-20	M	C	43.8	0.51	0.52	0.98	0.96
-20	M	A	54.4	0.56	0.53	1.03	1.04
-20	T	C	50.5	0.53	0.51	1.06	0.98
-20	T	A	86.8	0.51	0.51	0.98	0.96
-20	T	A	53.0	0.51	0.51	0.98	0.98

Testing was conducted at two temperatures (28°F and -20°F), on asphalt and concrete pavement, on which salt brine was applied as an anti-icer, then four successive applications of water were added to create a change in water depth over time. To determine the accuracy of each sensors' water/ice depth readings, the actual amount of water added at each step was recorded.

The average amounts of water added in each successive step (1, 2, 3, and 4) appear below:

- The average water depth added in the first application was 0.52 ± 0.016 mm.
- The average water depth added in the second application was 0.51 ± 0.008 mm.
- The average water depth added in the third application was 1.01 ± 0.027 mm.
- The average water depth added in the fourth application was 0.99 ± 0.028 mm.

The goal was that for the subsequent calibration of the RCM411 and MARWIS sensors, water depth readings should be 0.00 mm for water film height. After the first application of water, the sensors should provide a reading in the range of 0.52 mm. Following the second application of water, they should provide a reading in the range of 1.04 mm. Following the third application, they should provide a reading in the range of 2.05 mm. Following the fourth and final application of water, they should provide a reading in the range of 3.04 mm for water film height/ice depth, as shown in Figure 16.

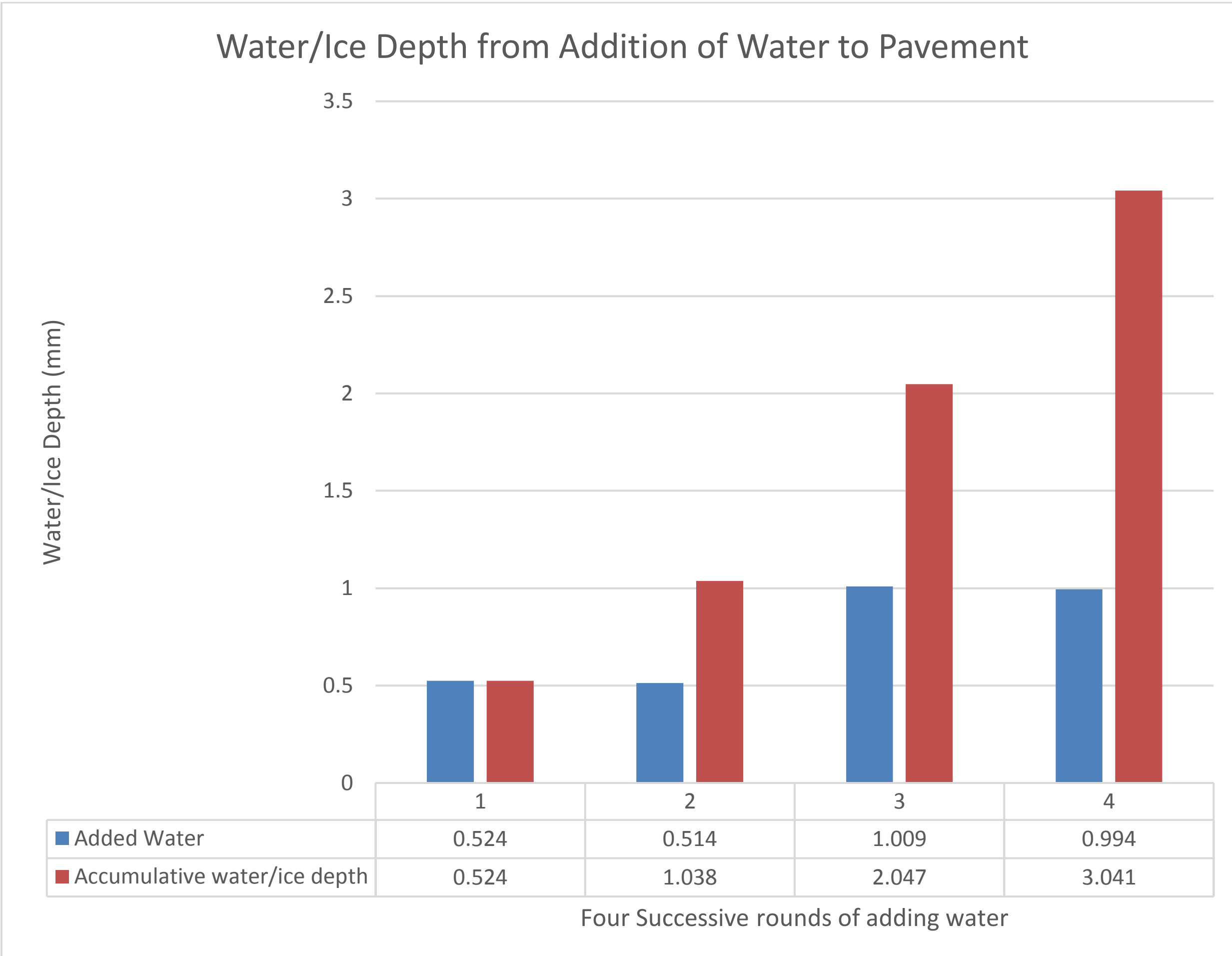


Figure 16. A graph of the water applied with each addition and the successive amounts of water/ice depth from each reading

The results of what each sensor reported are discussed below.

Teconer RCM411

Note that the RCM411 reports water depth data in mm and does not report ice depth. As is shown in Figure 17, following the addition of water an increase in water depth is observed, followed by a steady decline in water depth until the next addition of water. The data were collected from an asphalt sample at air and pavement temperature of 28°F.

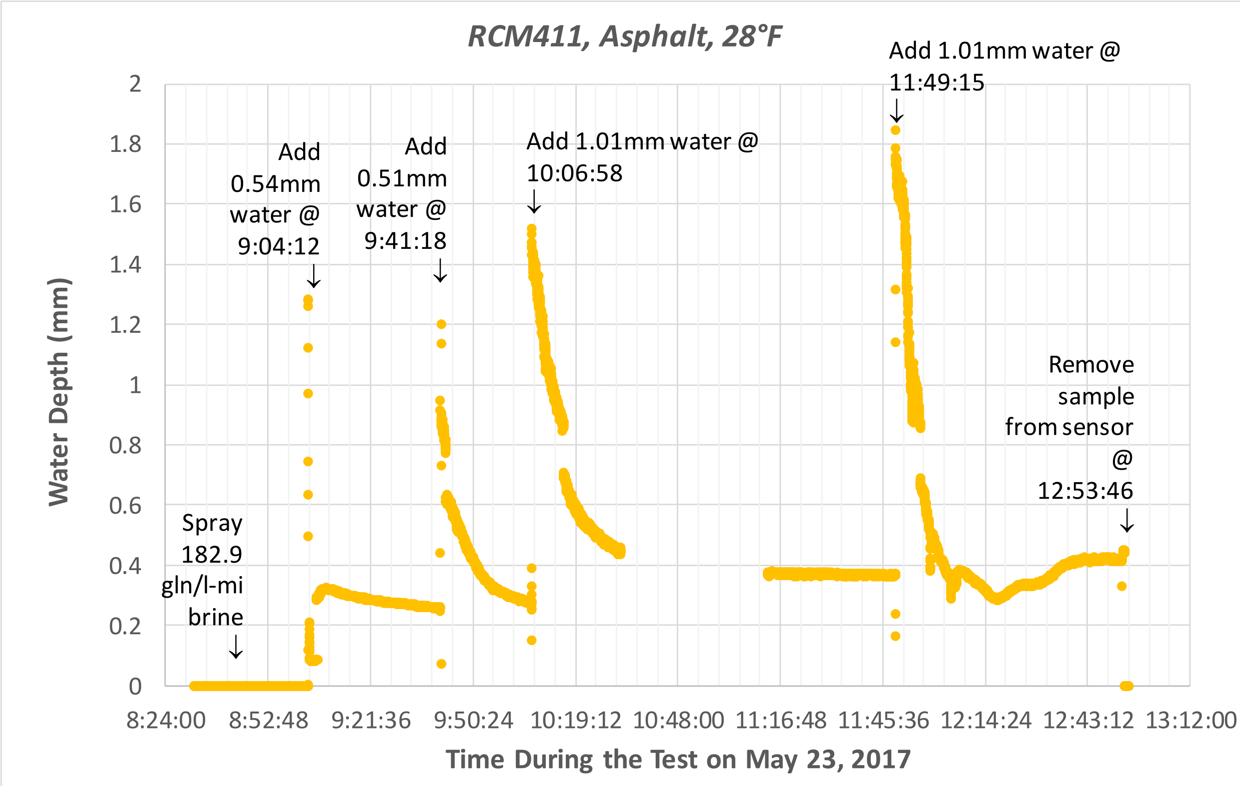


Figure 17. Water depth data reported by the Teconer RCM411 at calibrations, after anti-icing, and application of water four times (0.54mm, 0.51mm, 1.01mm, and 1.01mm), with data collected from an asphalt sample at an air and pavement temperature of 28°F

To look further into the data, Figure 18 shows the same data in box plots reporting the mean water depth (mm), first quartile, and third quartile in which water depth data falls, and errors (whisker) bars report the 95% confidence interval of the water depth data. The upper whisker represents the highest water depth at each application, and the lower whisker represents the lowest water depth at each application.

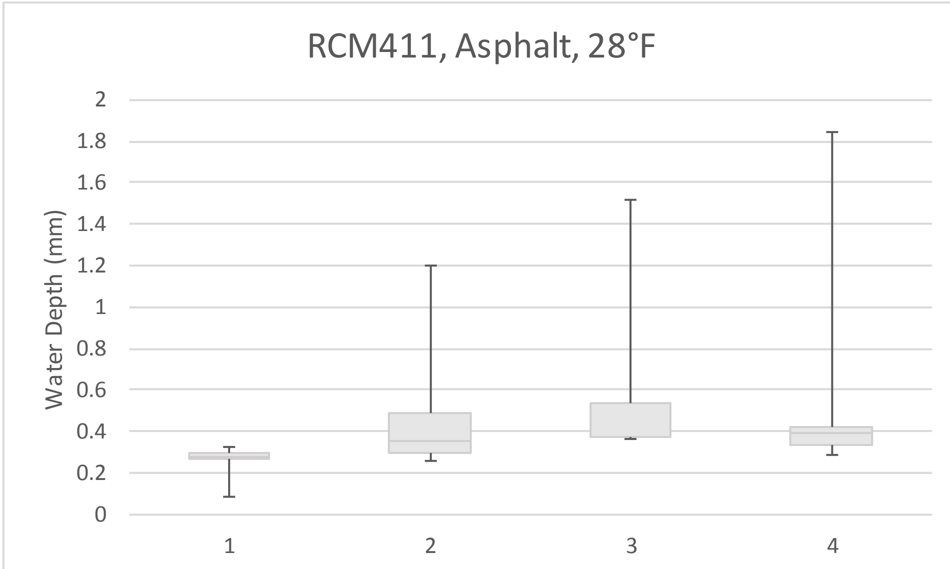


Figure 18. Box plot of water/ice depth data measured by the Teconer RCM411 sensor on asphalt at 28°F

From Figure 17 and Figure 18, it can be observed that following applications of water, the initial water depth is high, in the range of the added water, and over time the water depth decreases as it freezes.

It is interesting to note that while the RCM411 does not provide ice depth data, the lowest water depth values reported between the additions of water never reach zero for water depth. This indicates that either a thin film of water remained between additions of water, or possibly that the sensors are picking up the ice layer over the pavement surface.

From Figure 17, it can be seen that the RCM411 sensor's response to changes in water depth occurs almost instantaneously, with the initial increase in water depth detected immediately, followed by a quick 10 second or less transition to the steady decrease in water depth as it freezes.

Figure 19 reports the same data as average (and standard deviation) of the water depth (mm) measured by the RCM411 for each stage of testing: calibration, anti-icing, additions 1, 2, 3, and 4 of water, 0.00 mm, 0.00 mm, 0.27±0.05 mm, 0.41±0.15 mm, 0.52±0.26 mm, 0.48±0.30 mm, respectively (Table 6).

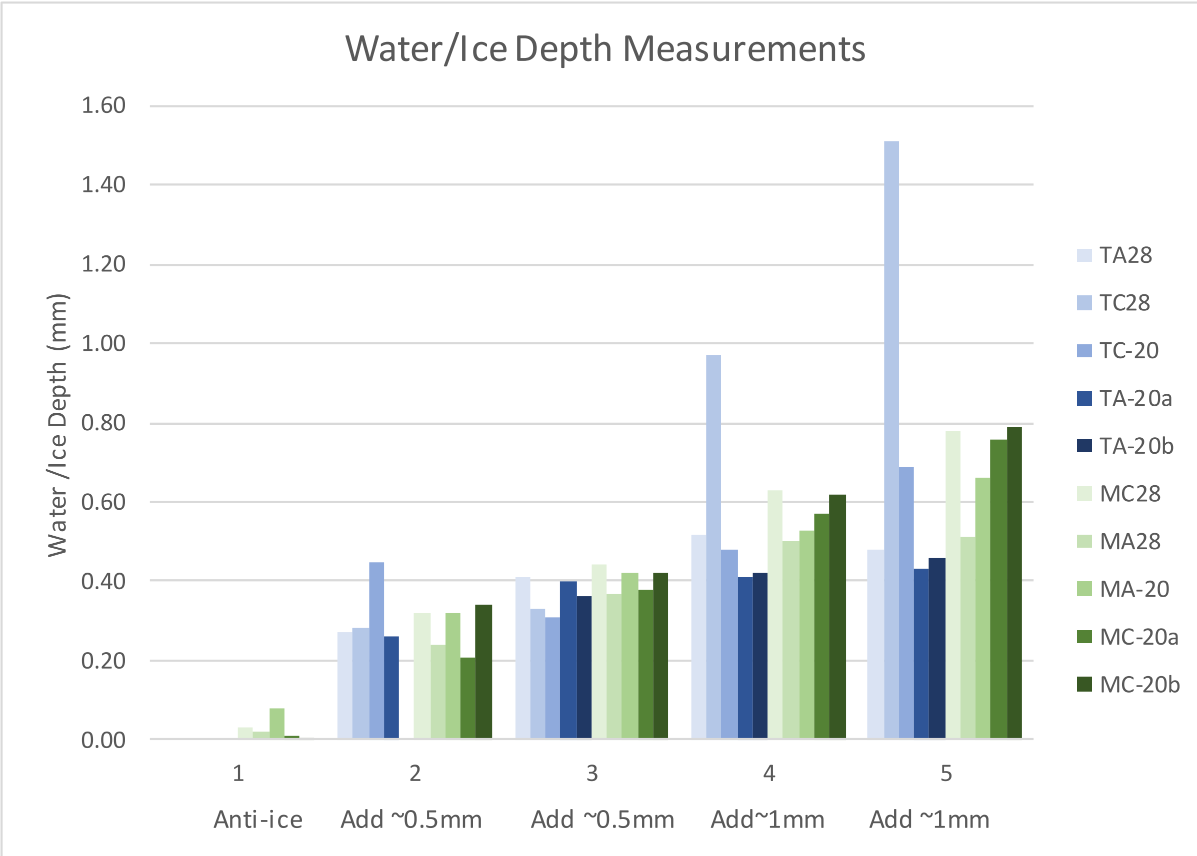


Figure 19. Water/Ice depth data measured using the RCM411 and MARWIS sensors, (T = Teconer RCM411, M = MARWIS, A = Asphalt sample, C = Concrete sample, 28 = 28°F testing temperature, -20 = -20°F testing temperature

Table 6. Summary table of water/ice depth measurements from the Teconer RCM411 and MARWIS sensors presented by average and standard deviation of water/ice depth (mm) over the testing time of calibration, anti-icing, addition of water four times (approximately 0.5 mm, 0.5 mm, 1.0 mm, 1.0 mm of water, respectively)

				Water/Ice Depth (mm)											
				Calibration		Anti-ice (NaCl)		1		2		3		4	
Temp (°F)	Sensor (Marwis-M Teconer RCM411-T)	Pavement Type (Asphalt-A, Concrete–C)	Salt Brine Application Rate (gal/l-m)	Avg	StDev	Avg	StDev	Avg	StDev	Avg	StDev	Avg	StDev	Avg	StDev
28	T	A	182.9	0.00	0.00	-	-	0.27	0.05	0.41	0.15	0.52	0.26	0.48	0.30
28	T	C	84.5	0.00	0.00	-	-	0.28	0.08	0.33	0.22	0.97	0.64	1.51	0.76
28	M	C	53.2	0.003	0.003	0.03	0.02	0.32	0.15	0.44	0.13	0.63	0.14	0.78	0.09
28	M	A	33.9	0.00	0.00	0.02	0.02	0.24	0.05	0.37	0.07	0.50	0.07	0.51	0.05
-20	T	C	50.5	0.00	0.00	-	-	0.45	0.06	0.31	0.01	0.48	0.13	0.69	0.15
-20	Ta	A	86.8	0.00	0.00	-	-	0.26	0.06	0.40	0.02	0.41	0.09	0.43	0.11
-20	Tb	A	53.0	0.00	0.00	-	-	-	-	0.36	0.02	0.42	0.07	0.46	0.12
-20	M	A	54.4	0.00	0.00	0.08	0.04	0.32	0.02	0.42	0.04	0.53	0.04	0.66	0.05
-20	Mb	C	60.9	0.00	0.00	0.006	0.001	0.34	0.09	0.42	0.05	0.62	0.08	0.79	0.08
-20	Ma	C	43.8	0.00	0.00	0.01	0.005	0.21	0.04	0.38	0.03	0.57	0.08	0.76	0.07

The values show a general increase in water depth over time with each successive application of water. These values are also shown in Figure 19 as TA28. The values reported by the RCM411 reflect each new application of water with fair accuracy. But, because the water then turns to ice, the water depth decreases significantly, so the average water depth for each additional application appears to be low.

Figure 20 and Figure 21 show the same test, but with the RCM411 recording water depth from a concrete sample. Figure 21 shows the mean water depth (mm), first quartile, and third quartile in which water depth data falls, and errors (whisker bars) report the 95% confidence interval of the water depth data.

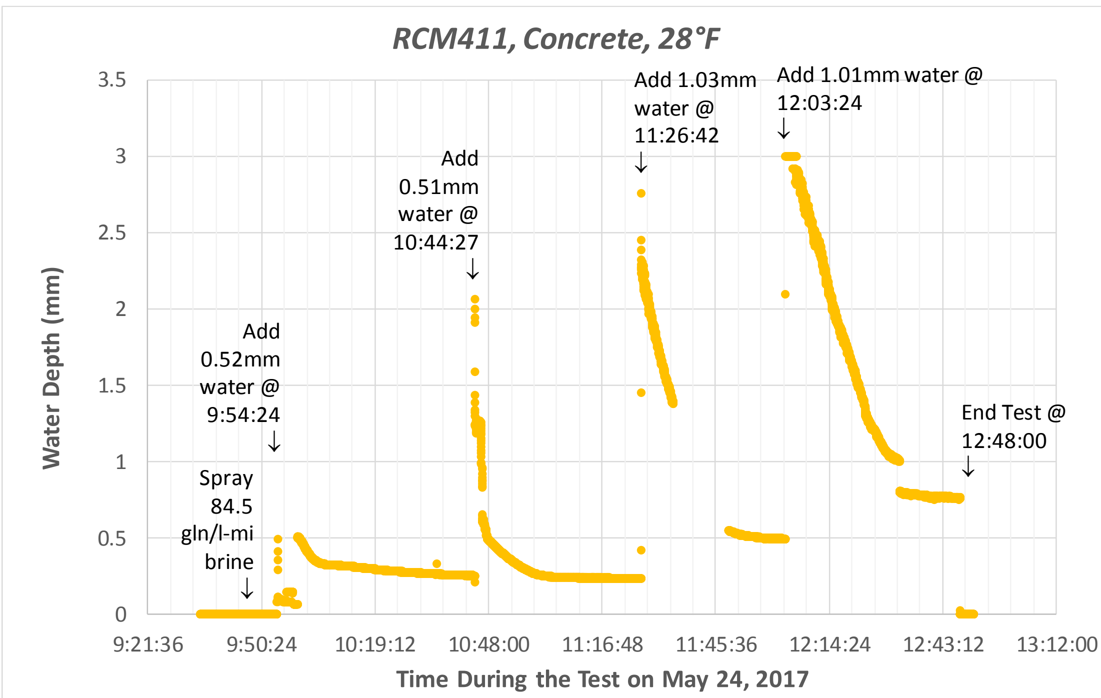


Figure 20. Water depth data reported by the Teconer RCM411 at calibrations, after anti-icing, and then following the application of water four times (0.52mm, 0.51mm, 1.03mm, and 1.01mm), with data collected from a concrete sample at an air and pavement temperature of 28°F

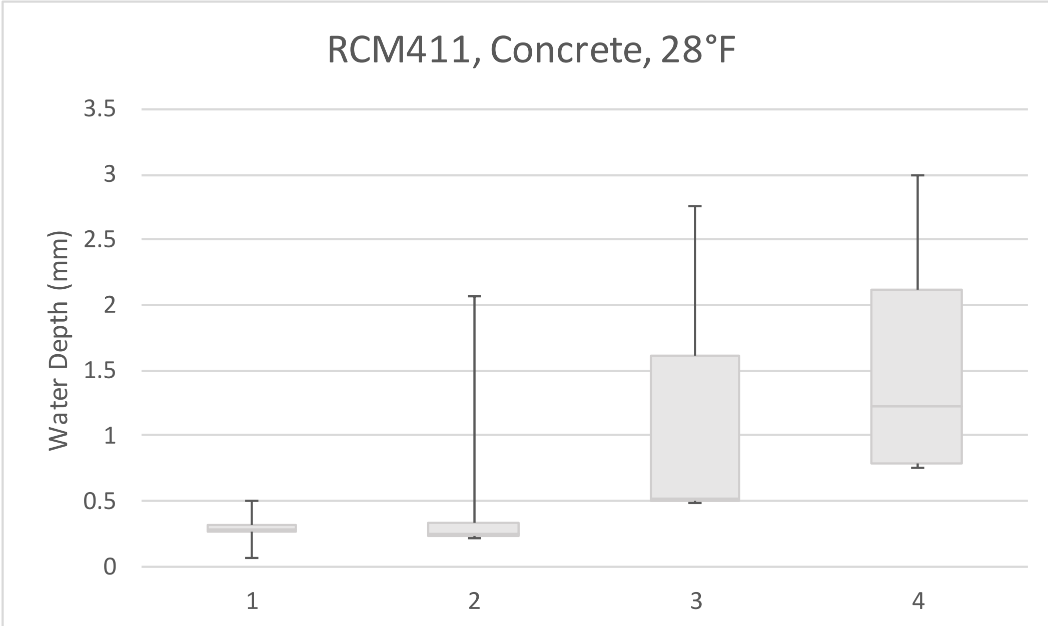


Figure 21. Box plot of water/ice depth data measured by the Teconer RCM411 sensor on concrete at 28°F

Note the general trend of the RCM411 sensors reading water depth fairly accurately when the water is first added but over time, as the water freezes and becomes ice, the water depth measurements decreasing. Looking at the average and standard deviation of TC28, Figure 19 shows calibration, anti-icing, additions 1, 2, 3, and 4 of water, 0.00 mm, 0.00 mm, 0.28±0.08 mm, 0.33±0.22 mm, 0.97±0.64 mm, 1.51±0.76 mm, respectively (Table 6). The values show an increase in water depth with each successive application of water, more so for the concrete sample than the asphalt sample.

Observations of how the RCM411 reported water depth on asphalt (Figure 22 and Figure 23) and concrete (Figure 24 and Figure 25) samples at -20°F show a trend similar to the RCM411 sensor readings. Water depth is shown fairly accurately when the water is first added, but over time, as the water freezes and becomes ice, the water depth measurements decrease. Figures 23 and 25 show the mean water depth (mm), first quartile, and third quartile in which water depth data falls, and errors (whisker bars) report the 95% confidence interval of the water depth data.

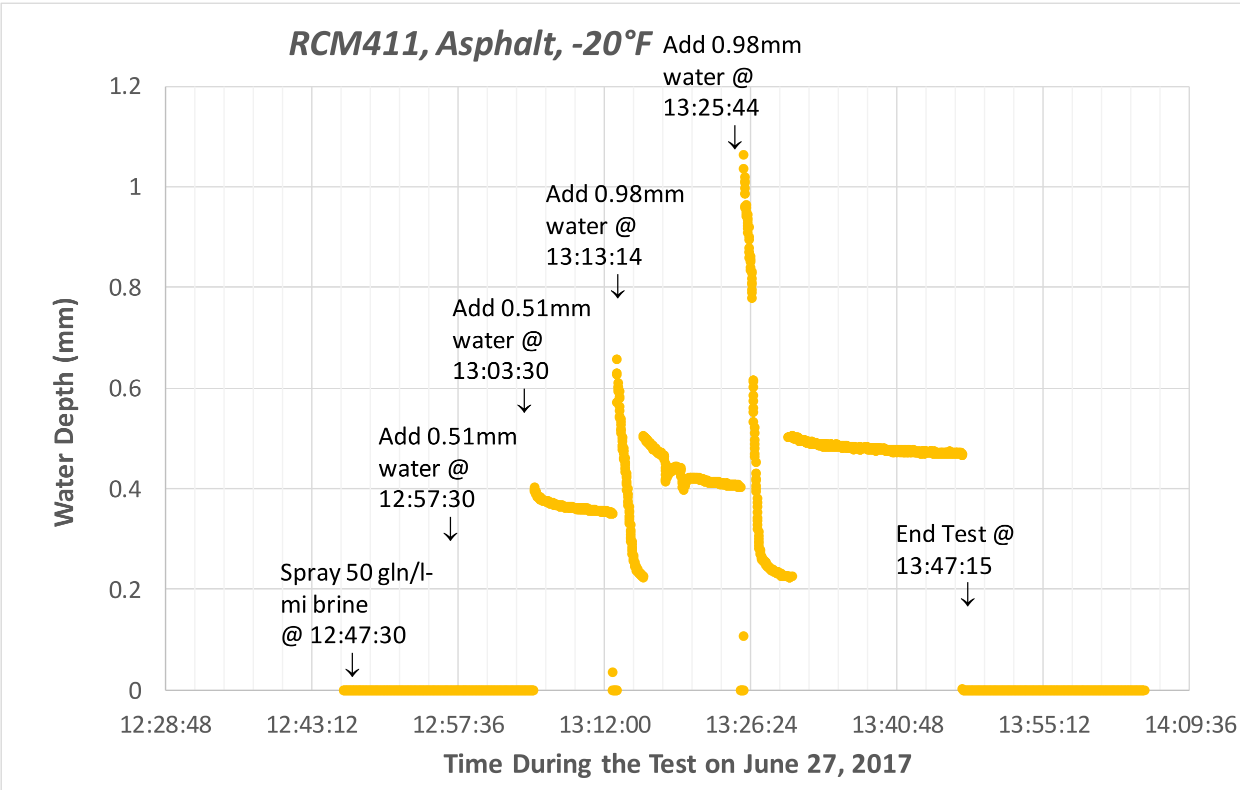


Figure 22. Water depth data reported by the Teconer RCM411 at calibrations, after anti-icing, and application of water four times (0.51 mm, 0.51 mm, 0.98 mm, and 0.98 mm), with data collected from an asphalt (b) sample at an air and pavement temperature of -20°F

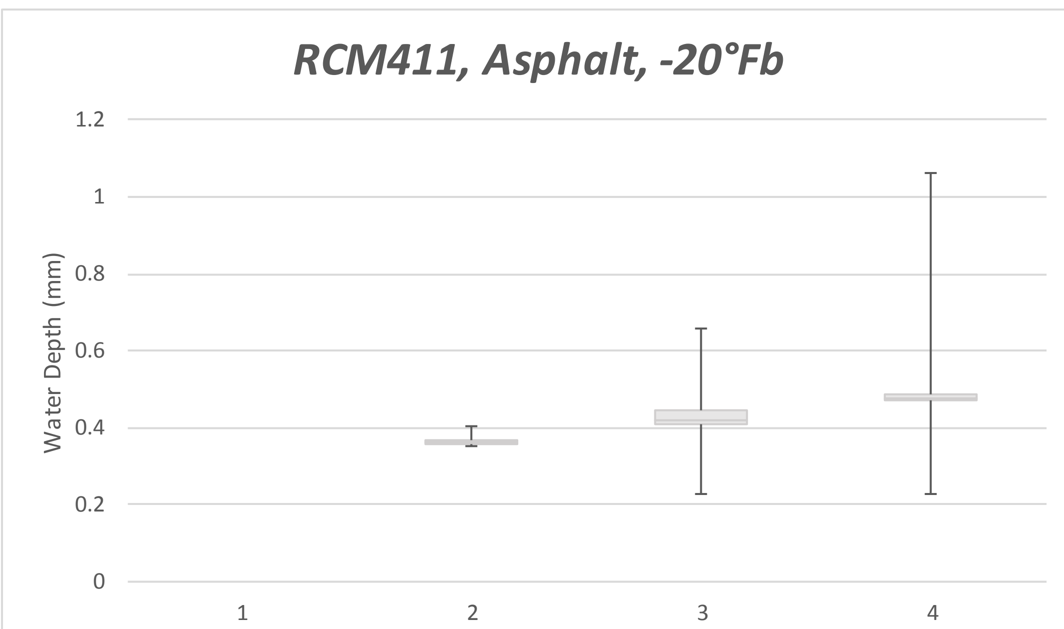


Figure 23. Box plot of water/ice depth data measured by the Teconer RCM411 sensor on asphalt (b) at -20°F

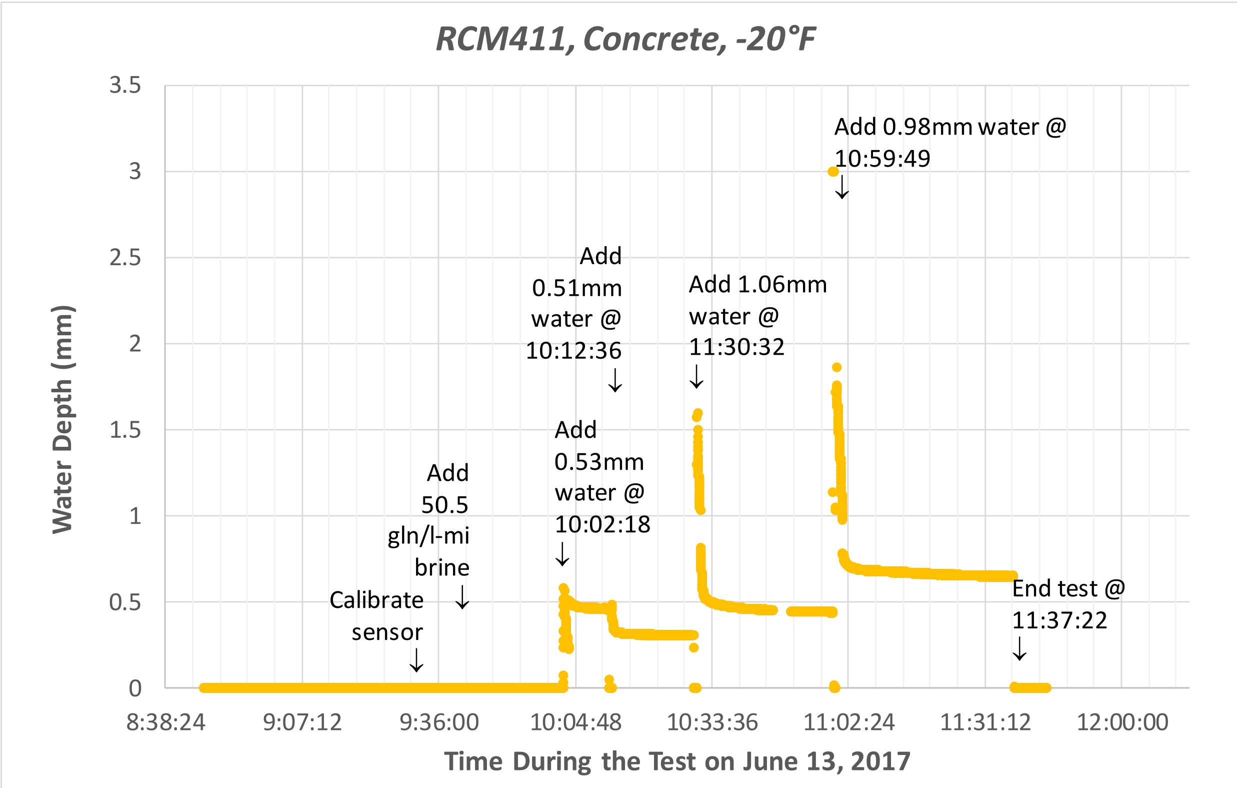


Figure 24. Water depth data reported by the Teconer RCM411 at calibrations, after anti-icing, and application of water four times (0.51 mm, 0.53 mm, 1.06 mm, and 0.98 mm), with data collected from a concrete sample at an air and pavement temperature of -20°F

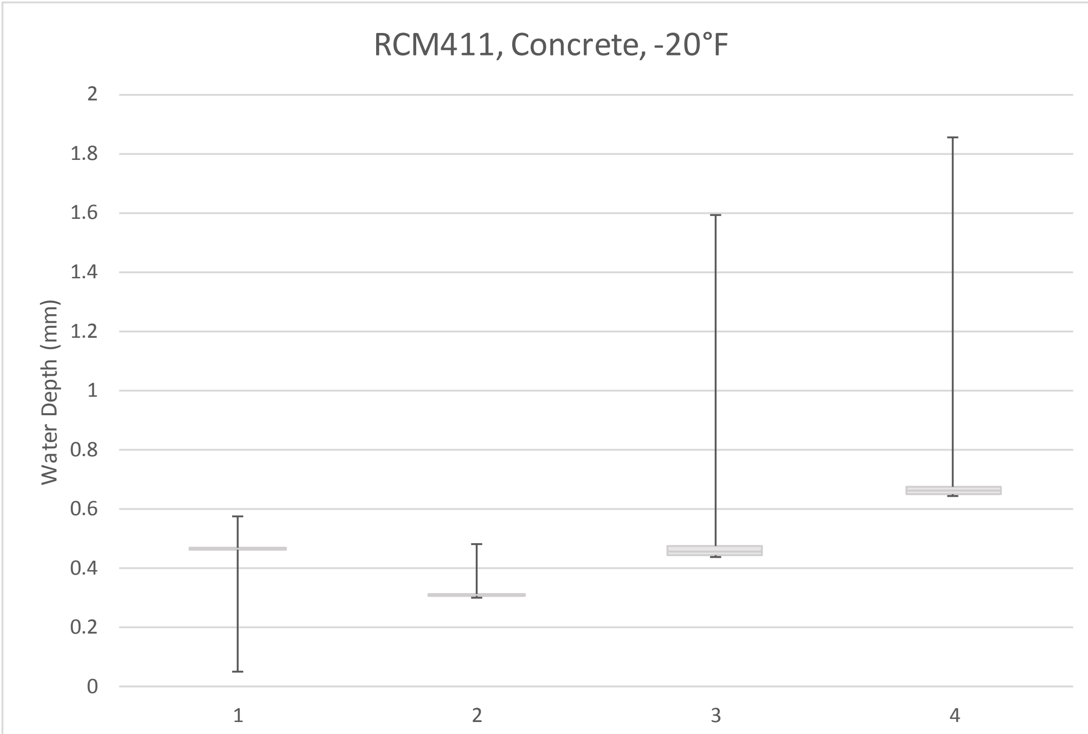


Figure 25. Box plot of water/ice depth data measured by the Teconer RCM411 sensor on concrete at -20°F

For both the asphalt and concrete samples, the RCM411 sensor did not register the first addition of water at -20°F. This is likely because the air and pavement temperatures were so cold that the water froze almost immediately (which was observed in the lab facility). The average water depth after each successive application is shown in Figure 19 as TA-20 and TC-20 and in Table 6. For both the asphalt and concrete samples, an increase in water depth was observed with each successive application of water. The general trend continued for the average water depth measured with each successive application to the concrete sample being higher than that on the asphalt sample.

Additional figures not presented in this section are found in Appendix A.

MARWIS

The MARWIS sensor measures water and ice depth which are reported in mils and µm. To simplify the comparison between data sets, the MARWIS data were converted from mils to mm using the following equation:

(mil x 2.54)/100 = mm

Upon initial observation of the MARWIS water/ice depth data versus the RCM411, the MARWIS sensor shows greater sensitivity to water application. This was seen in the MARWIS detection of the application of the anti-icer in each round of testing, on asphalt and concrete samples at 28°F and -20°F, which the RCM411 was unable to do. Figure 19 shows the average water/ice depths from anti-icing application (MA28, MC28, MA-20, MC-20a,b). Table 6 presents the average and standard deviation of water/ice depth with each successive application including the water depth from the addition of anti-icer.

As was observed in the RCM411 data, the MARWIS sensor fairly accurately records the water depth following successive applications, but also shows a decrease in water depth over time as the water freezes and becomes ice (Figure 26 and Figure 28). This is validated by the additional data collected by the MARWIS sensor, which reports ice percent (%) on the pavement surface. Figure 27 shows that during each application of liquid (anti-icer, and successive additions of water) the ice percent drops, but then steadily increases back to 100% ice on the pavement surface until more liquid is added. Figure 28 shows the mean water depth (mm), first quartile, and third quartile in which water depth data falls, and errors (whisker bars) report the 95% confidence interval of the water depth data.

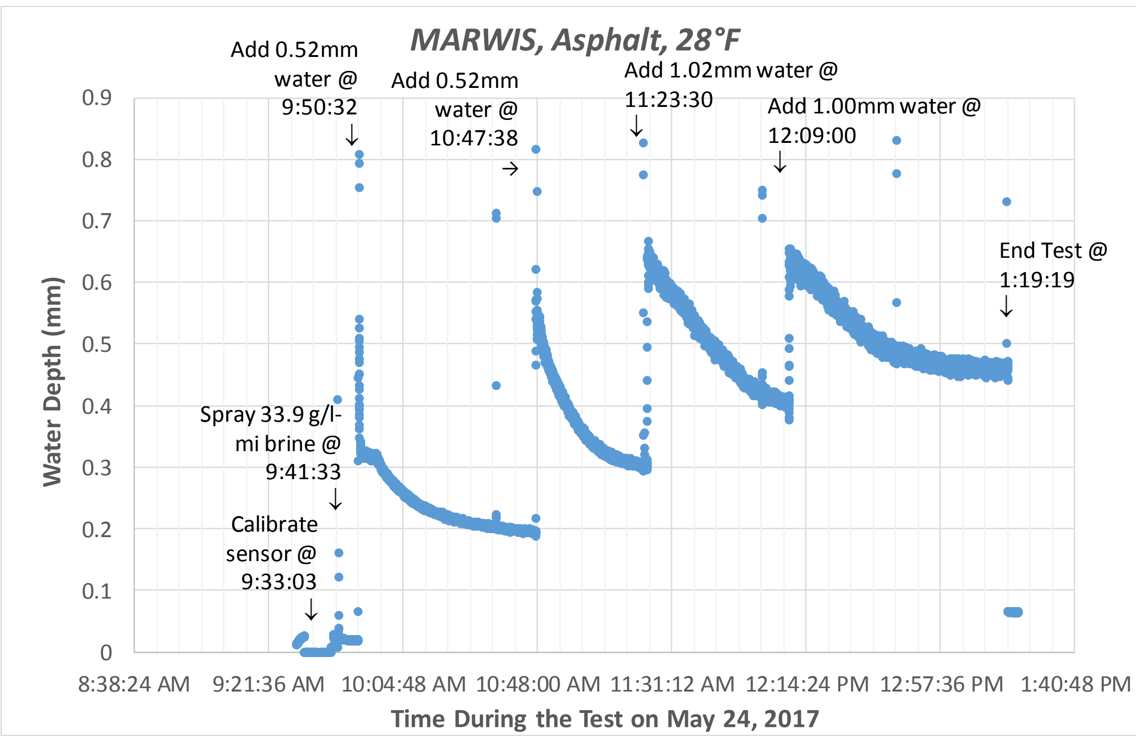


Figure 26. Water/Ice depth data reported by the MARWIS at calibration, after anti-icing, and application of water four times (0.52 mm, 0.52 mm, 1.02 mm, and 1.00 mm), with data collected from an asphalt sample at an air and pavement temperature of 28°F

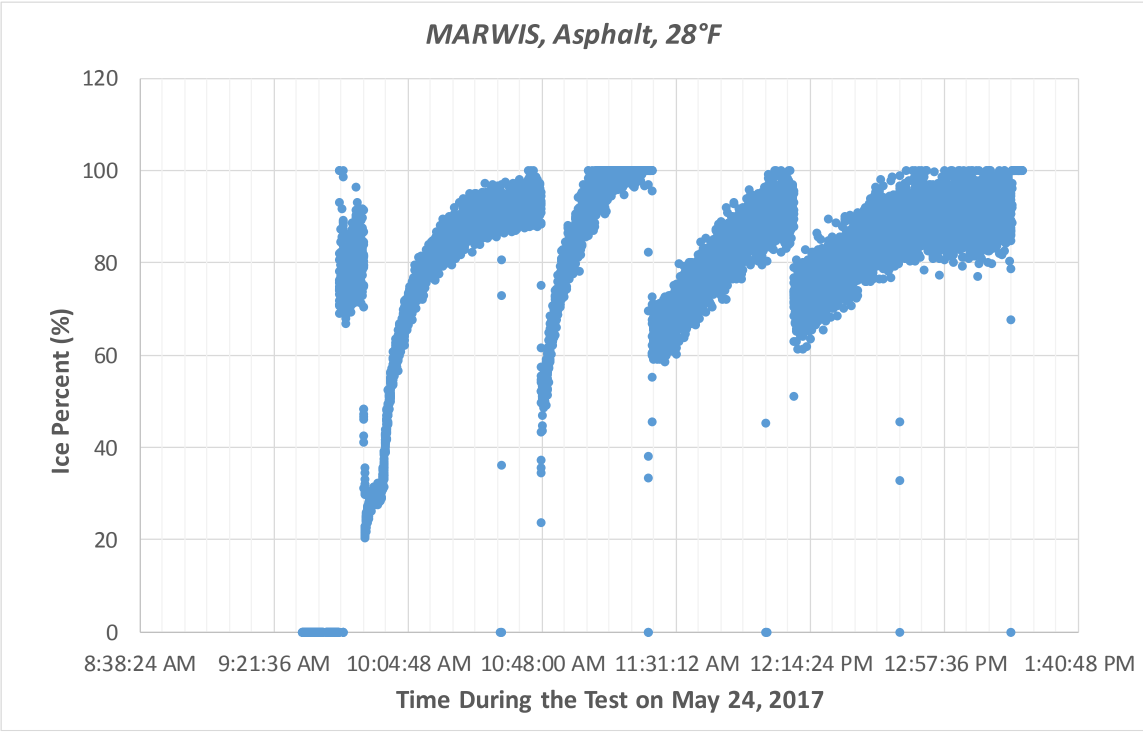


Figure 27. Ice Percent (%) measured by the MARWIS sensor on asphalt pavement at 28°F test temperature

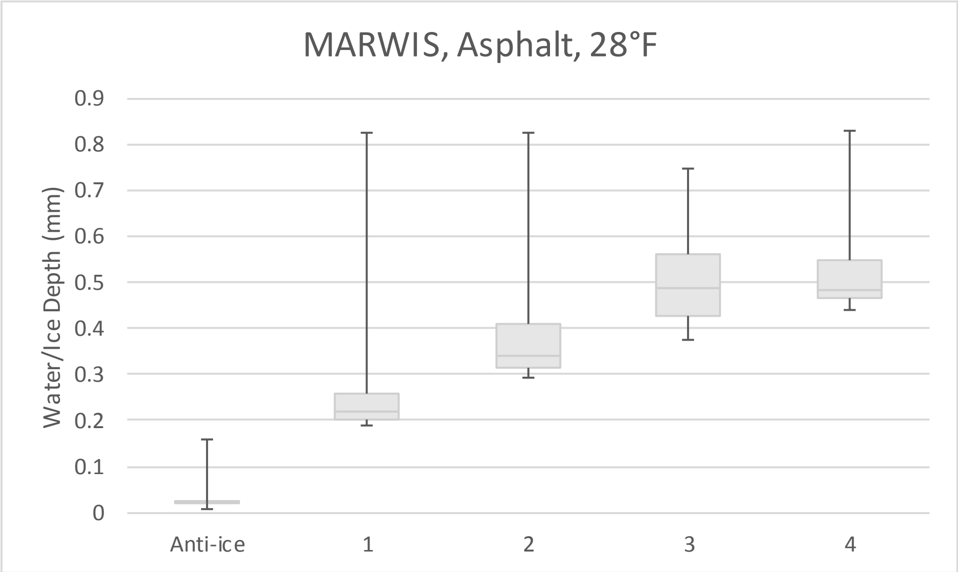


Figure 28. Box plot of water/ice depth data measured by the MARWIS sensor on asphalt at 28°F

The same trend was observed for all pavement types and at both 28°F and -20°F. Additional figures showing ice percent for all MARWIS testing can be found in Appendix A.

When the MARWIS water/ice depth readings on both the asphalt (Figure 26 and Figure 28) and concrete samples (Figure 29 and Figure 30) were compared, an increase in water depth was observed with each successive application of water. Figure 30 shows the mean water depth (mm), first quartile, and third quartile in which water depth data falls, and errors (whisker bars) report the 95% confidence interval of the water depth data.

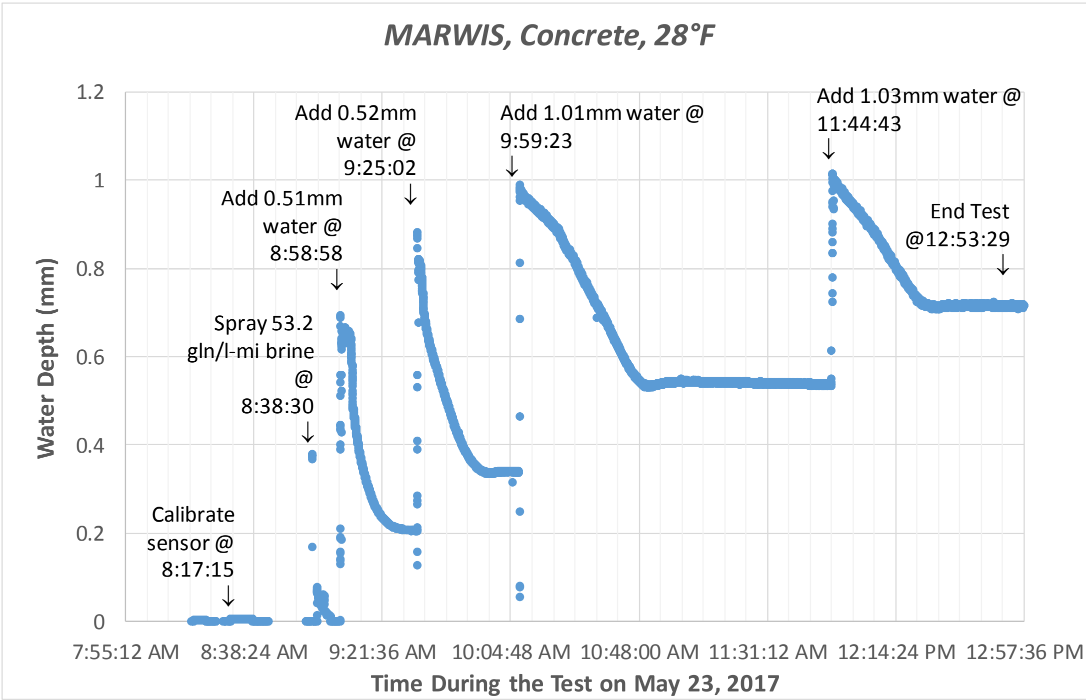


Figure 29. Water/Ice depth data reported by the MARWIS at calibration, after anti-icing, and application of water four times (0.51 mm, 0.52 mm, 1.01 mm, and 1.03 mm), with data collected from a concrete sample at an air and pavement temperature of 28°F

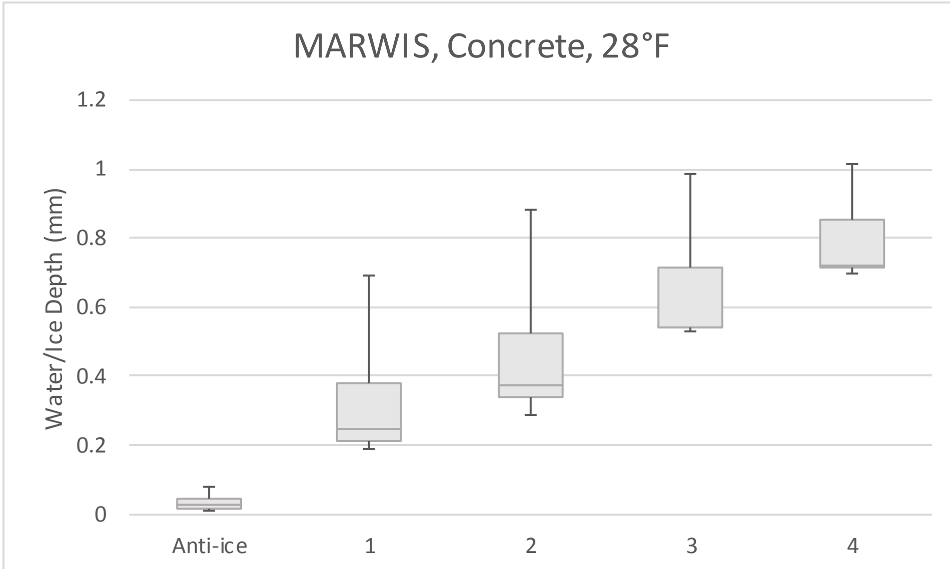


Figure 30. Box plot of water/ice depth data measured by the MARWIS sensor on concrete at 28°F

Additionally, the concrete sample had higher water/ice depth readings than the asphalt samples (Figure 19). This is also true at the colder temperature of -20°F (and is shown in Table 6).

The MARWIS unit was able to detect all applications of liquid and anti-icer as well as successive water applications during testing at -20°F on both concrete and asphalt samples (Figure 31 and Figure 33), where the RCM411 was unable to detect the application of anti-icer and the first addition of water on both pavement types at the same temperature. Figure 32 and Figure 34 shows the mean water depth (mm), first quartile, and third quartile in which water depth data falls, and errors (whisker bars) report the 95% confidence interval of the water depth data for data collected from asphalt and concrete samples, respectively.

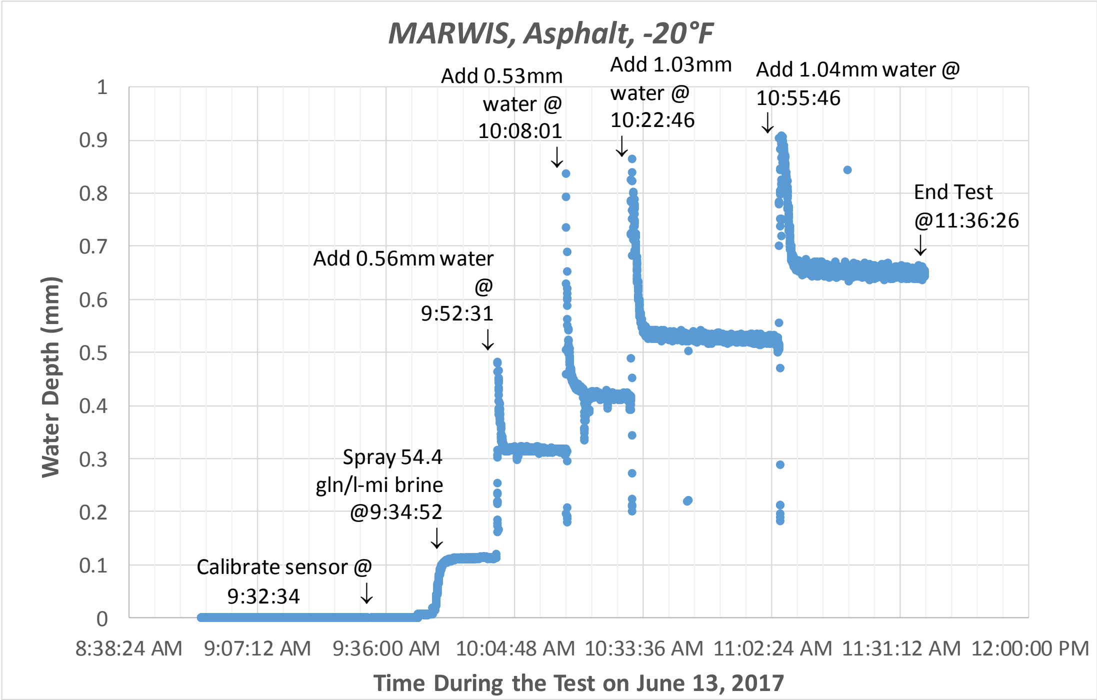


Figure 31. Water/Ice depth data reported by the MARWIS at calibration, after anti-icing, and application of water four times (0.56 mm, 0.53 mm, 1.03 mm, and 1.04 mm), with data collected from an asphalt sample at an air and pavement temperature of -20°F

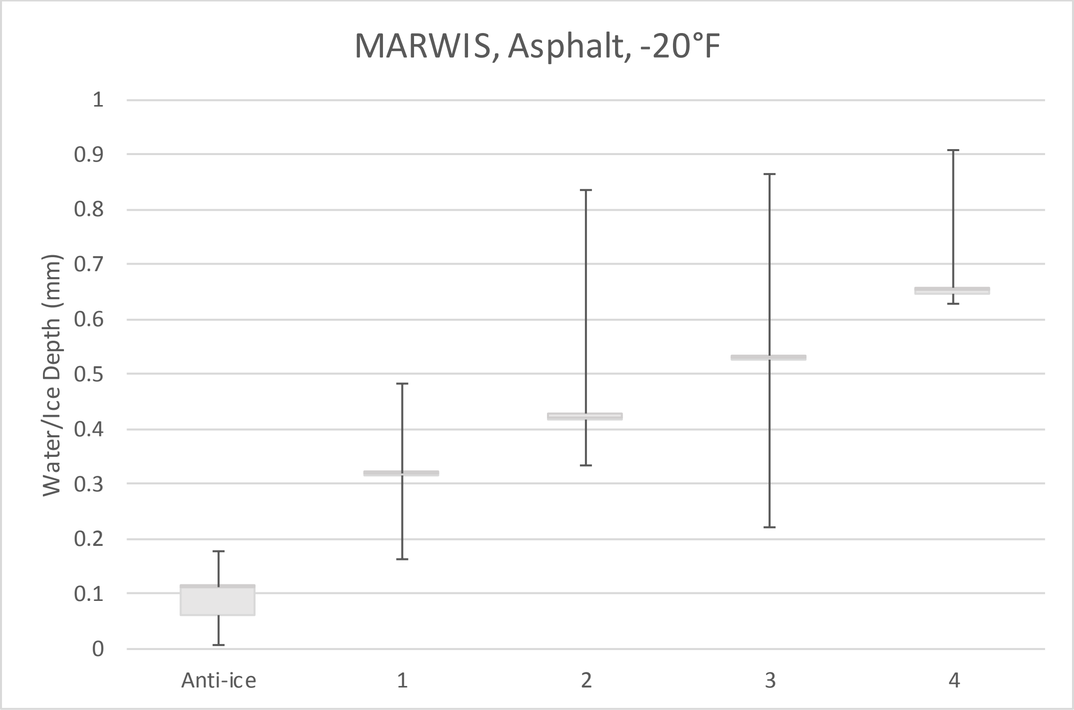


Figure 32. Box plot of water/ice depth data measured by the MARWIS sensor on asphalt at -20°F

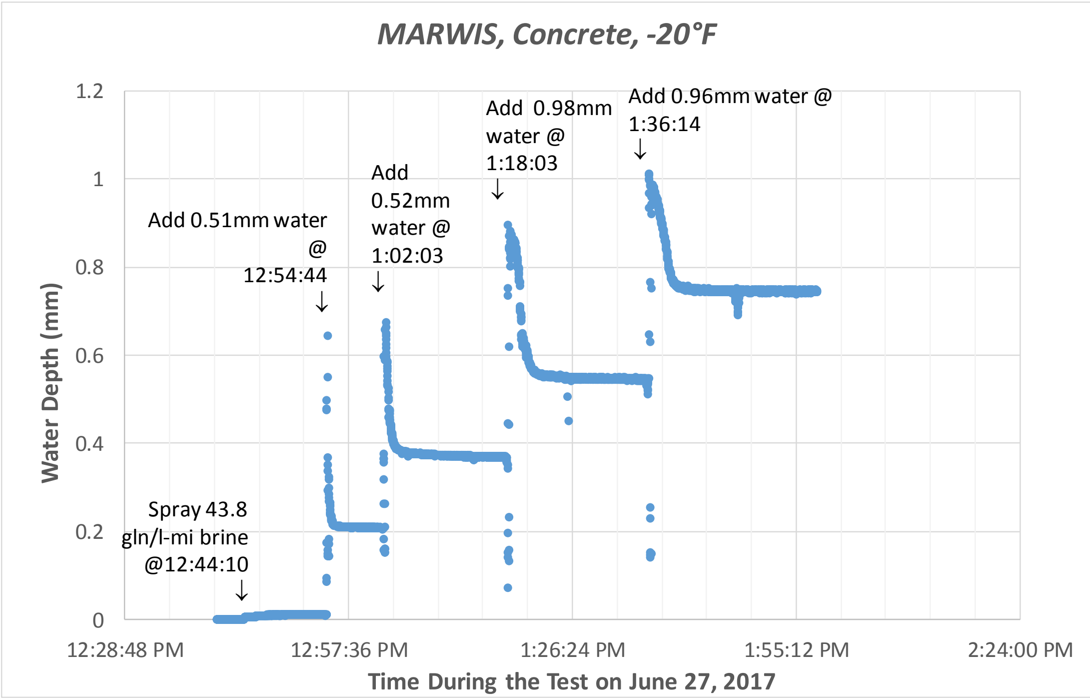


Figure 33. Water/Ice depth data reported by the MARWIS at calibration, after anti-icing, and application of water four times (0.51 mm, 0.52 mm, 0.98 mm, and 0.96 mm), with data collected from a concrete sample at an air and pavement temperature of -20°F

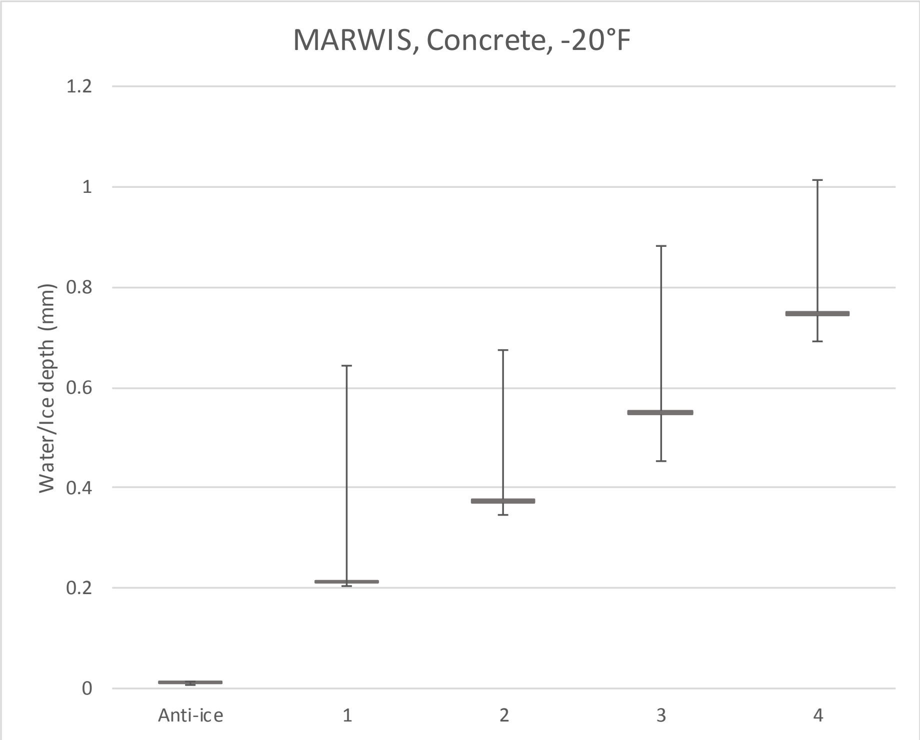


Figure 34. Box plot of water/ice depth data measured by the MARWIS sensor on concrete (a) at -20°F

Overall, the response time and reading of water depth from the RCM411 and MARWIS were instantaneous (0 to 4 seconds), but in a few instances, took up to 5 seconds.

Additional figures not presented in this section can be found in Appendix A.

Conclusions from the RCM411 water depth testing were as follows:

- The sensor fairly accurately detects the addition of liquid to the pavement surface when it is first added. But over time as the water freezes, the water depth decreases so that the accumulated water depth is less than what it would be in the absence of freezing.
- The sensor detected greater water depth on the concrete samples than on the asphalt samples.
- The sensor could not detect the first addition of water at very cold temperatures (-20°F) because it froze instantly, and the sensor detects water depth, but not ice depth, on the pavement surface.

Conclusions from the MARWIS water/ice depth testing were as follows:

- The MARWIS sensor is more sensitive to water application on pavement than the RCM411.
- The sensor detected greater water and ice depth on the concrete samples than on the asphalt samples.

Snow and Trafficking Testing

The Teconer RCM411 and MARWIS sensors recorded or calculated the following values during snow and trafficking testing that will be discussed in this section:

MARWIS:

- Water/ice depth
- Friction
- Pavement surface temperature
- Ice percent
- Road condition class (calculated)

Teconer RCM411:

- Water depth
- Friction
- Pavement surface temperature
- Road surface state (calculated)

The goals of the laboratory testing were to ascertain how well each sensor reports these values and presents the information as usable data, identify any data reporting lag times, and observe trends in the testing.

Table 4 summarizes the experimental conditions for the snow and trafficking testing. Testing was conducted at 28°F on asphalt and concrete pavement on which salt brine was applied as an anti-icer. Snow was added, compacted, trafficked, and then plowed/scraped off. The plowed/scraped off snow was collected, and chloride concentration of the snow was measured. Measurements were collected at each step in the testing, and the collected data are reported as follows.

Water/Ice Depth

Figure 35 and Figure 36 show water/ice depth data that the MARWIS sensor collected from the snow and trafficking testing on concrete and asphalt pavement.

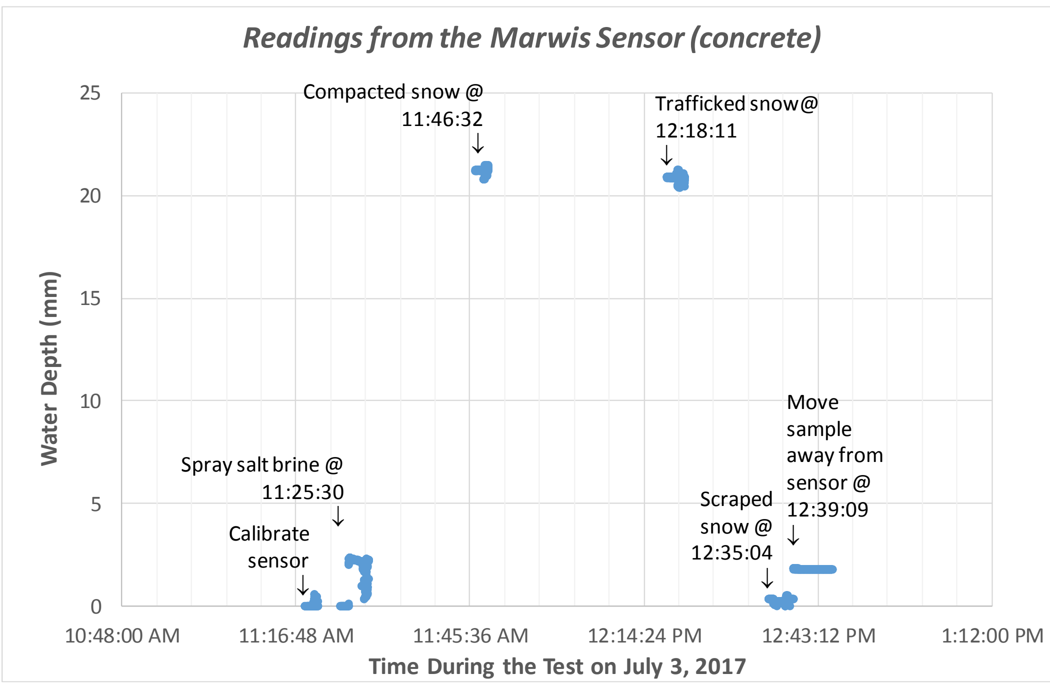


Figure 35. Water/ice depth data reported by the MARWIS throughout the snow trafficking testing (calibration, after anti-icing, addition of snow and compacting, trafficking, and plow/scraping of snow), with data collected from a concrete sample at an air and pavement temperature of 28°F

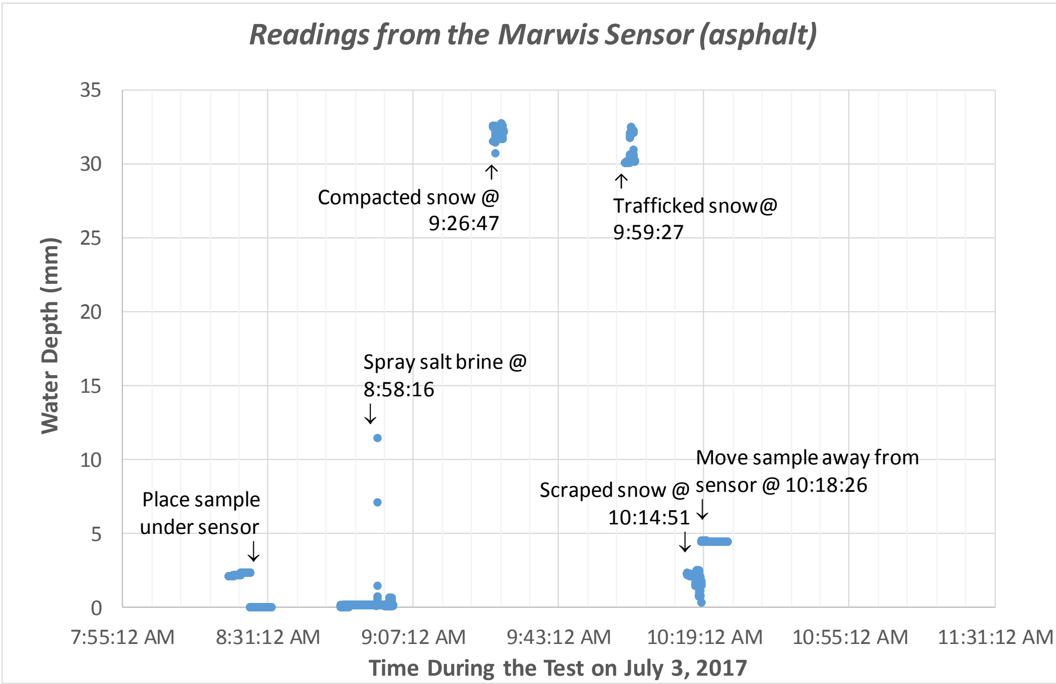


Figure 36. Water/ice depth data reported by the MARWIS throughout the snow trafficking testing (calibration, after anti-icing, addition of snow and compacting, trafficking, and plow/scraping of snow), with data collected from an asphalt sample at an air and pavement temperature of 28°F

As was observed in the previous section, which details water/ice depth measurements, the MARWIS sensor does a good job of quickly assessing the change from dry pavement to the application of salt brine, the addition of snow, and plowing/scraping of snow. There was not a discernable difference in water/ice depth following the application of snow with compaction or trafficking. After plowing/scraping off the snow, the sensor quickly reported the change in water/ice depth. Additional figures showing water/ice depth data from the MARWIS sensor on both asphalt and concrete pavement can be found in Appendix B.

Figure 37 and Figure 38 show water depth data collected from the Teconer RCM411 sensor during snow and trafficking testing on concrete and asphalt pavement.

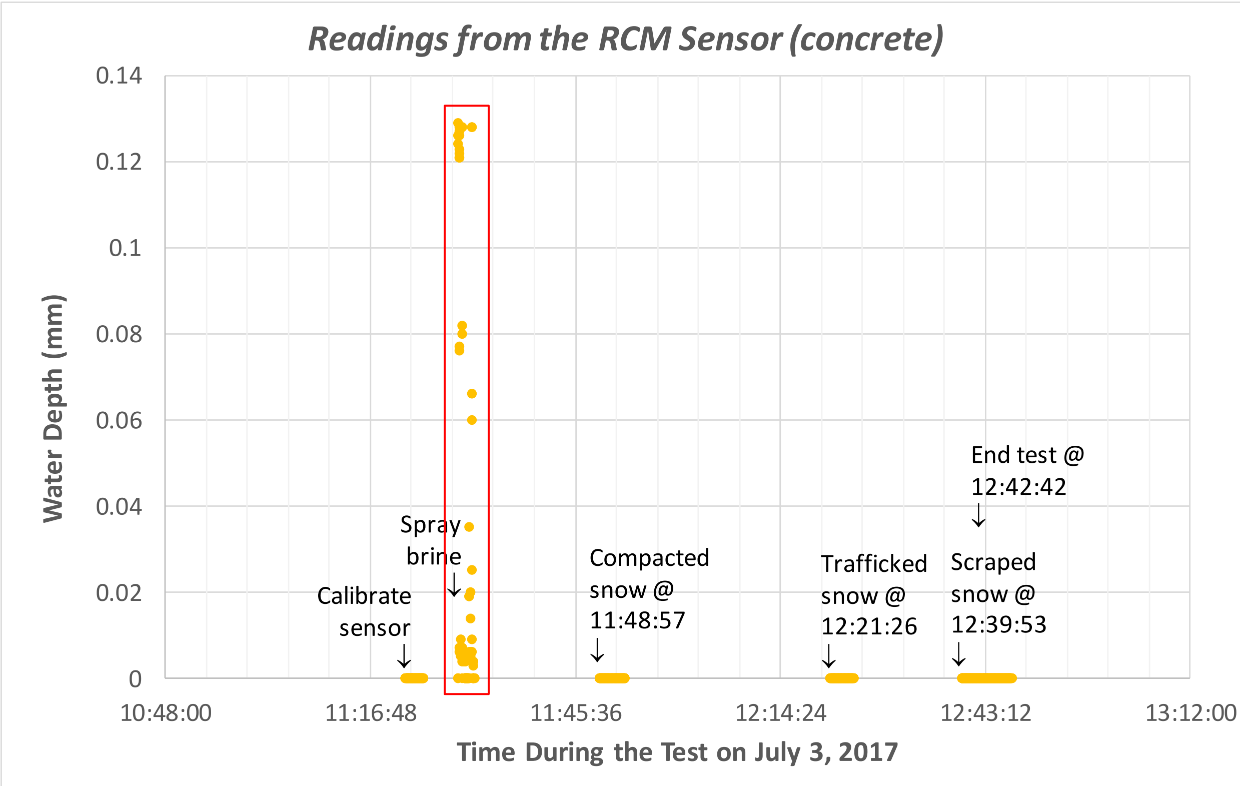


Figure 37. Water depth data reported by the Teconer RCM411 throughout the snow trafficking testing (calibration, after anti-icing, addition of snow and compacting, trafficking, and plow/scraping of snow), with data collected from a concrete sample at an air and pavement temperature of 28°F

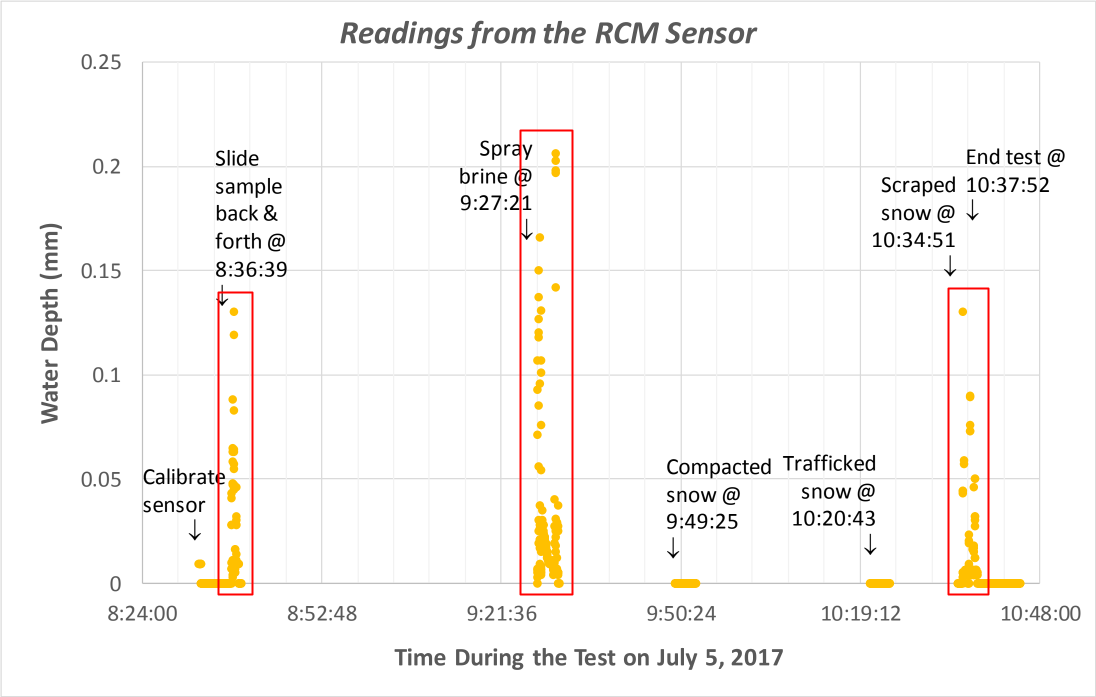


Figure 38. Water depth data reported by the Teconer RCM411 throughout the snow trafficking testing (calibration, after anti-icing, addition of snow and compacting, trafficking, and plow/scraping of snow), with data collected from an asphalt sample at air and pavement temperature of 28°F

The RCM411 sensor detected application of the salt brine, which is interesting because this sensor was unable to detect anti-icer application in the previously reviewed water depth testing. The water depth data reported are highly variable (blocked in red, Figure 37 and Figure 38. The RCM411 was not able to detect the presence of the compacted and trafficked snow, with the exception of Figure 39 which appears to show the detection of the loose snow (circled in blue), but once the snow was compacted, the water depth value drops to almost zero (mm).

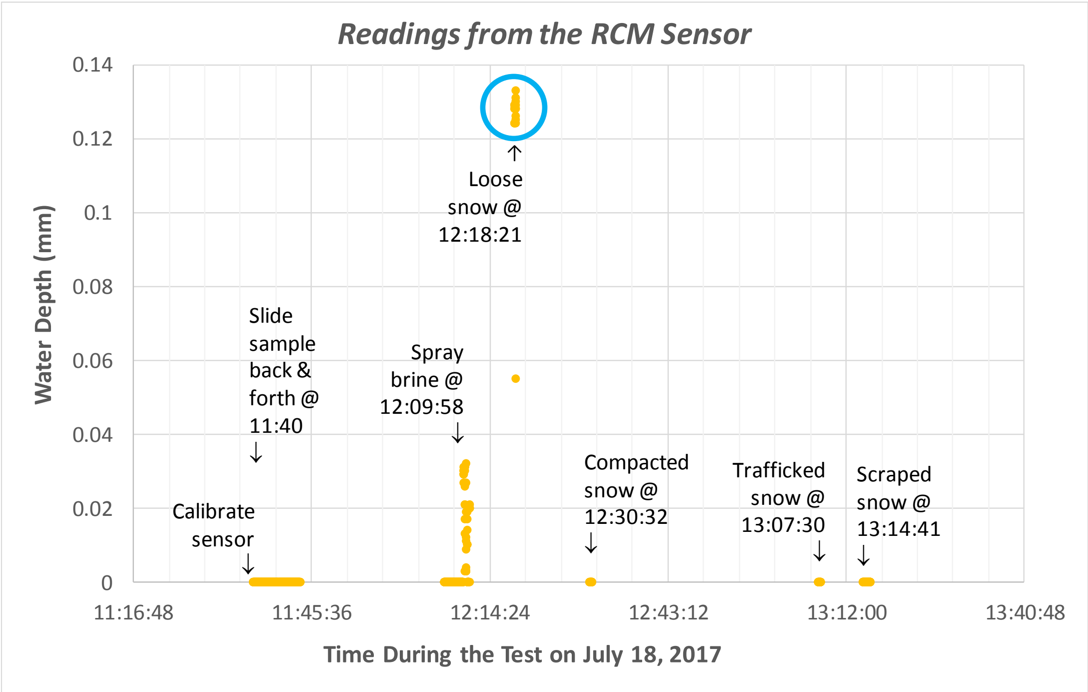


Figure 39. Water depth data reported by the Teconer RCM411 throughout the snow trafficking testing (calibration, after anti-icing, addition of snow and compacting, trafficking, and plow/scraping of snow), with data collected from a concrete sample at an air and pavement temperature of 28°F

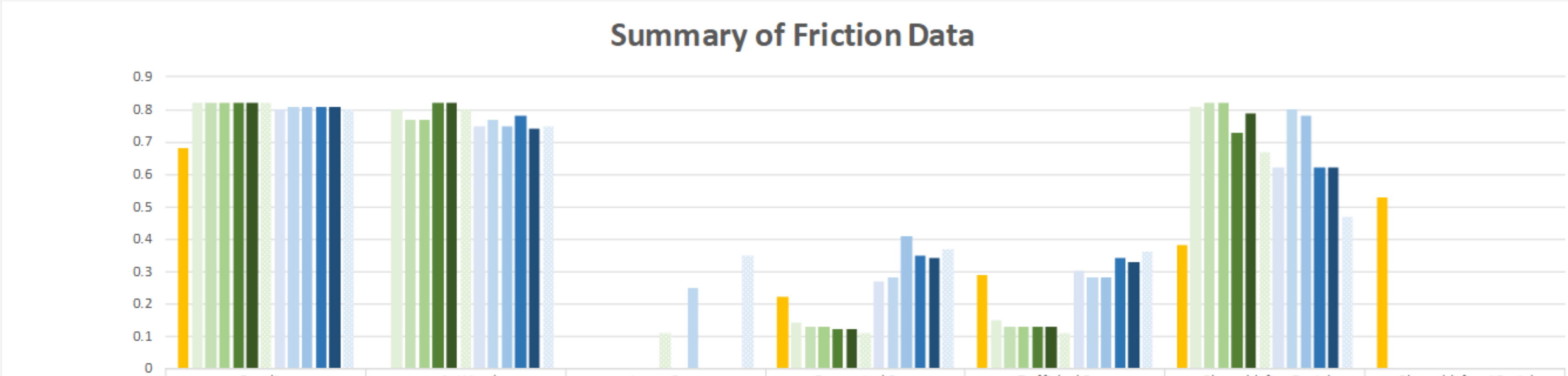
Additional figures showing water/ice depth data from the Teconer RCM411 sensor on both asphalt and concrete pavement can be found in Appendix B.

Conclusions from the water/ice depth testing with snow and trafficking were as follows:

- The three sensing elements from the RCM411 sensor were capable of reliably detecting the change in pavement surface conditions under this investigated scenario.
- The response time was almost immediate for both sensors (0 to 4 seconds).
- The water/ice depth data reported by the MARWIS were very precise and tightly clustered.
- When water was detected by the RCM411 sensor, the data were variable, suggesting a greater sensitivity in the data reported by this sensor.

Friction

The MARWIS sensor measures friction in addition to many other values and is marketed as a mobile RWIS that measures many additional parameters. The RCM411 was designed as a mobile friction measuring device that provides additional values. To compare the friction values reported by both the MARWIS and RCM411, static friction was also measured. Figure 40 provides a summary of average friction data from static friction measurements and friction measured using the MARWIS, and Teconer RCM411 sensors.



	Baseline	Anti-iced	Loose Snow	Compacted Snow	Trafficked Snow	Plowed (after 7 min)	Plowed (after 13 min)
Static Friction	0.68			0.22	0.29	0.38	0.53
MARWIS (7/3, C)	0.82	0.80		0.14	0.15	0.81	
MARWIS (7/18, C)	0.82	0.77		0.13	0.13	0.82	
MARWIS (7/27,C)	0.82	0.77		0.13	0.13	0.82	
MARWIS (7/3, A)	0.82	0.82		0.12	0.13	0.73	
MARWIS (7/5, A)	0.82	0.82		0.12	0.13	0.79	
MARWIS (7/31, A)	0.82	0.80	0.11	0.11	0.11	0.67	
RCM411 (7/3, C)	0.8	0.75		0.27	0.3	0.62	
RCM411 (7/18, C)	0.81	0.77	0.25	0.28	0.28	0.80	
RCM411 (7/27, C)	0.81	0.75		0.41	0.28	0.78	
RCM411 (7/3, A)	0.81	0.78		0.35	0.34	0.62	
RCM411 (7/5, A)	0.81	0.74		0.34	0.33	0.62	
RCM411 (7/31, A)	0.80	0.75	0.35	0.37	0.36	0.47	

Figure 40. Summary of average friction data from static friction measurements and friction measured using the MARWIS and Teconer RCM411 sensors over the testing conditions

The testing conditions comprised a 28°F pavement sample (baseline), anti-iced, loose snow (data only collected for some samples), compacted snow, trafficked snow, and plowed/scraped pavement (static friction was sampled here at 7 minutes and 13 minutes after plowing) on both asphalt (A) and concrete (C) pavement samples.

The average baseline friction values for all pavement types from both the MARWIS and Teconer RCM411 sensors are in the range of 0.8 to 0.82 μ. Friction values between 0.6 to 1.0 are generally considered good (green). Following the application of anti-icer (salt brine), the average friction values from the MARWIS and Teconer RCM411 sensors ranged from 0.75-0.8μ, remaining in the good (green) range. The addition of liquid anti-icer to the pavement samples decreased the friction values, but only slightly, and not in a statistically significant way. Once snow was applied, friction values dropped dramatically into the yellow and red zones for the loose snow on the pavement, the compacted snow on the pavement, and the trafficked snow on the pavement (Figure 40). This showed that addition of snow to the pavement decreases the friction on the pavement surface, creating a more slippery driving surface.

There does not appear to be a correlation between higher or lower friction values and concrete or asphalt pavement types throughout the various testing conditions. Figure 39 does show the high variability in the friction values between the various measurement methods, and the lower friction values reported by the MARWIS for loose, compacted, and trafficked snow compared to the static friction and Teconer RCM411 friction data. Once the pavement surface was plowed or scraped, all friction measurement methods showed an increase or improvement in friction, with most friction levels returning to the green (safe) zone.

Another interesting observation is the stepwise improvement or increase in friction shown in the static friction data with each change in pavement treatment conditions. The initial baseline friction values are high and drop significantly when measured on compacted snow, but then increase with trafficking and successive plowing over time (Figure 40).

Figure 41 and Figure 42 show the friction data reported by MARWIS for concrete and asphalt pavements over the course of the snow and trafficking experiment. Data were collected at air and pavement temperature of 28°F. The green shaded areas on the two figures are considered high friction values and safe driving conditions, the yellow is considered moderate friction and of concern, and the red is considered very low friction with loss of traction likely.

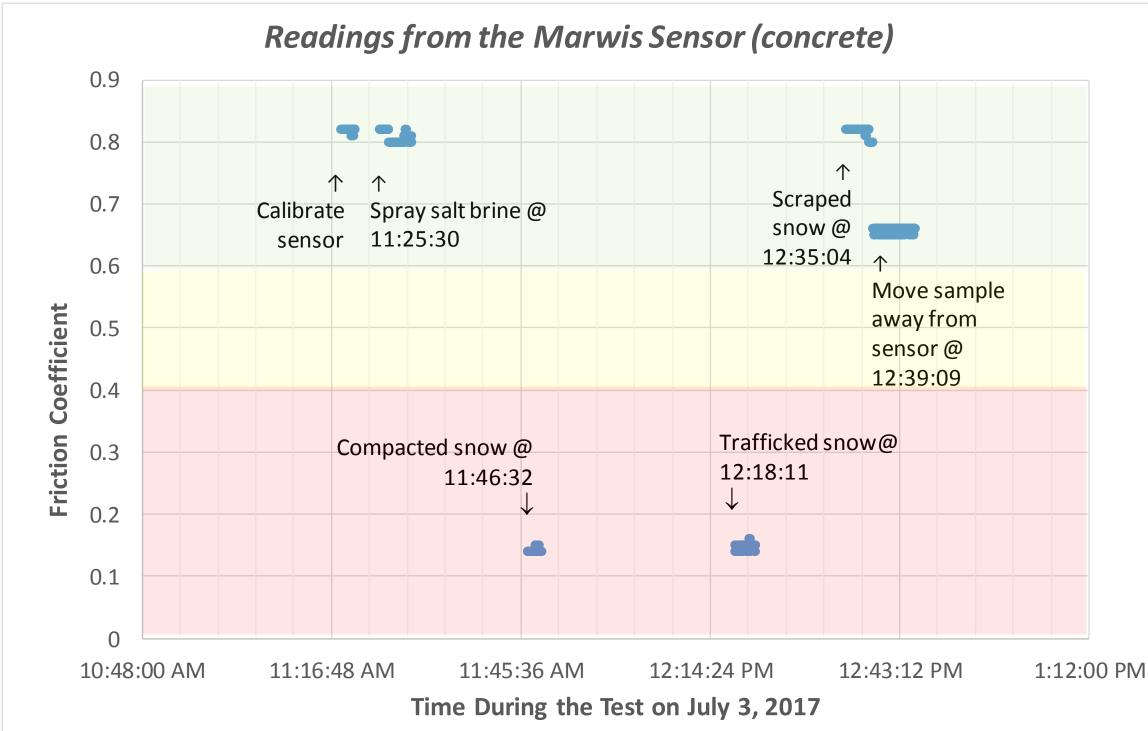


Figure 41. Friction coefficient data reported by MARWIS throughout the snow trafficking testing

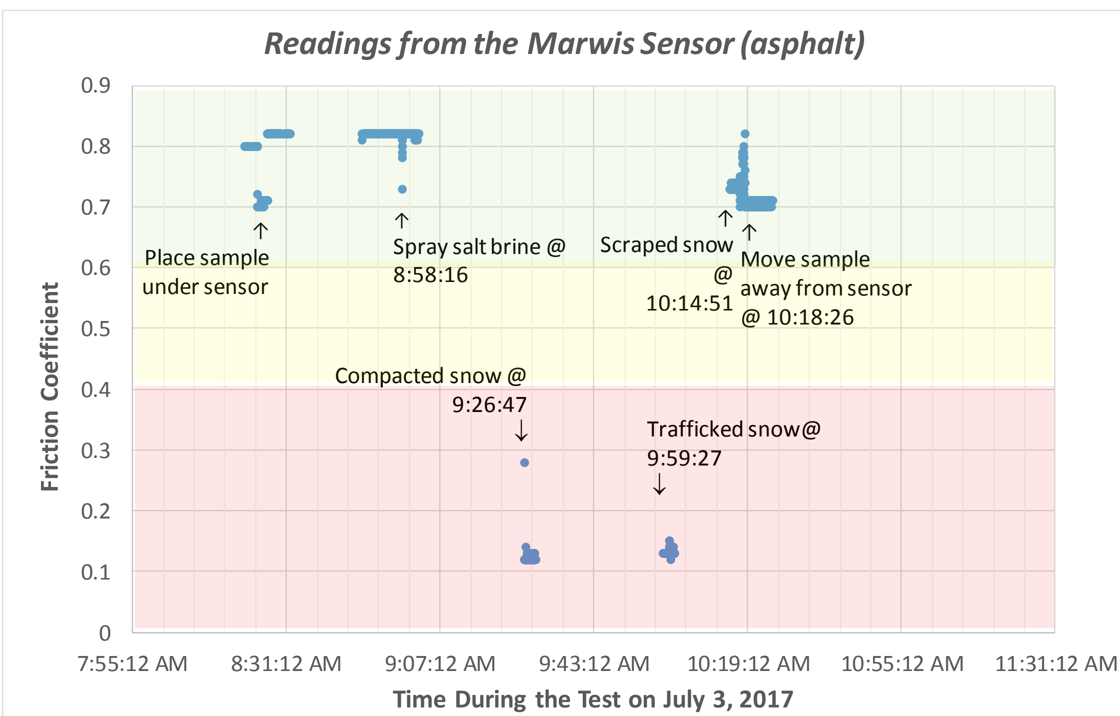


Figure 42. Friction coefficient data reported by MARWIS throughout the snow trafficking testing

Additional figures showing friction data from the MARWIS sensor on both asphalt and concrete pavements can be found in Appendix B.

Figure 43 and Figure 44 show the friction data over the course of the snow and trafficking experiment reported by the Teconer RCM411. Data were collected from concrete and asphalt samples at air and pavement temperature of 28°F. For both figures, the green shaded areas are considered high friction values and safe driving conditions, the yellow is considered moderate friction and of concern, and the red is considered very low friction with loss of traction likely.

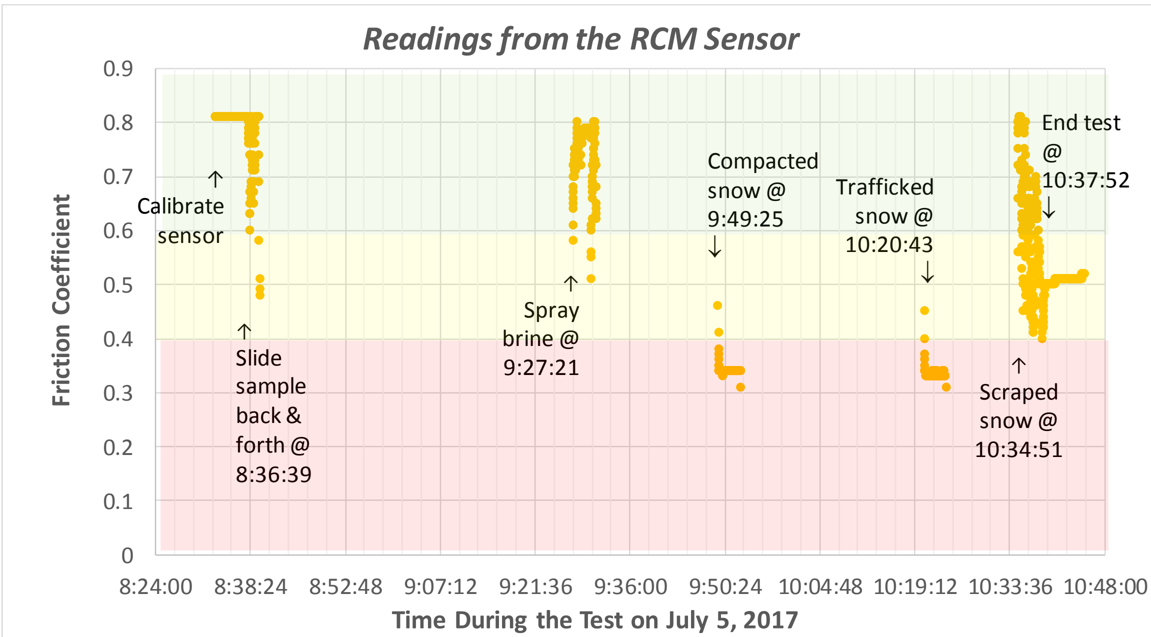


Figure 43. Friction coefficient data reported by the Teconer RCM411 throughout the snow trafficking testing

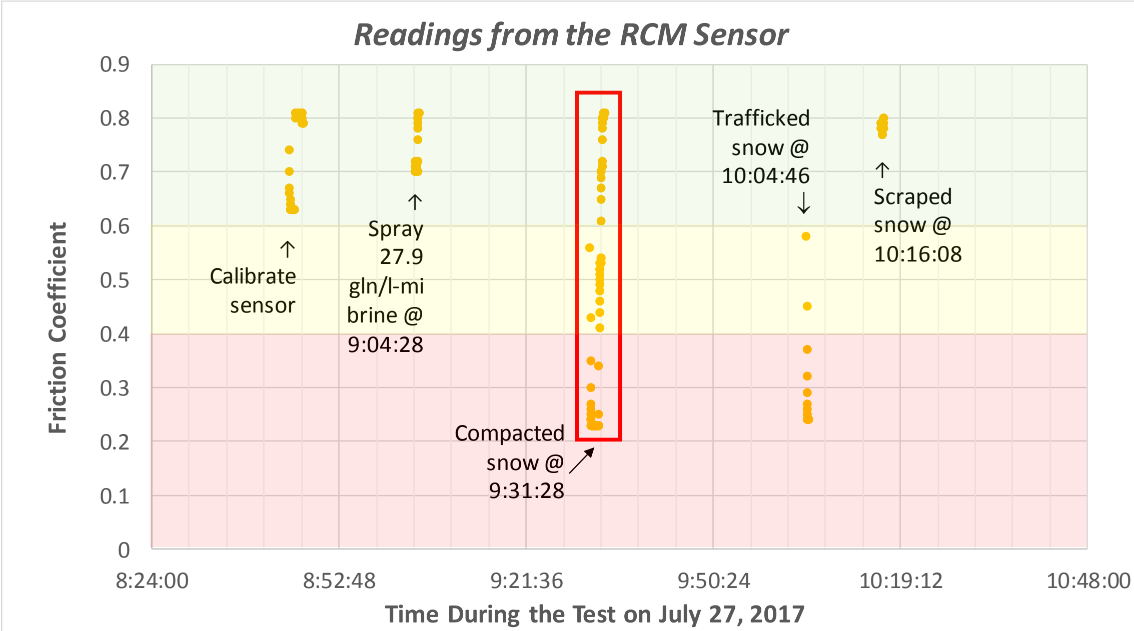


Figure 44. Friction coefficient data reported by the Teconer RCM411 throughout the snow trafficking testing

Friction readings appear to be sensitive and highly variable, with friction values decreasing with the application of snow and staying low throughout compaction and trafficking of snow, but then increasing as the snow is plowed/scraped off (Figure 43). Figure 44 shows the sensitivity, or variability, of the RCM411 sensor friction readings, reporting the range of friction values during the compaction of the sample (outlined in the red box), from low friction (slippery/unsafe) to higher friction (safer). This is interesting because friction values for trafficked snow (outlined in the blue box) also have a very high range of values. Returning to the data, the friction values go from moderate (0.55 to low (0.20) to high (0.8) during data collection for compaction but go from moderate (0.55) to low (0.25) during data collection for trafficking. Additional figures showing friction data from the Teconer RCM411 sensor on both asphalt and concrete pavements can be found in Appendix B.

Figure 45 and Figure 46 show box plots of all friction data collected by the MARWIS sensor from both concrete and asphalt pavements, respectively. The box plots present very precise friction data recorded during each test condition (e.g., baseline, anti-iced, compacted, trafficked, and plowed/scraped).

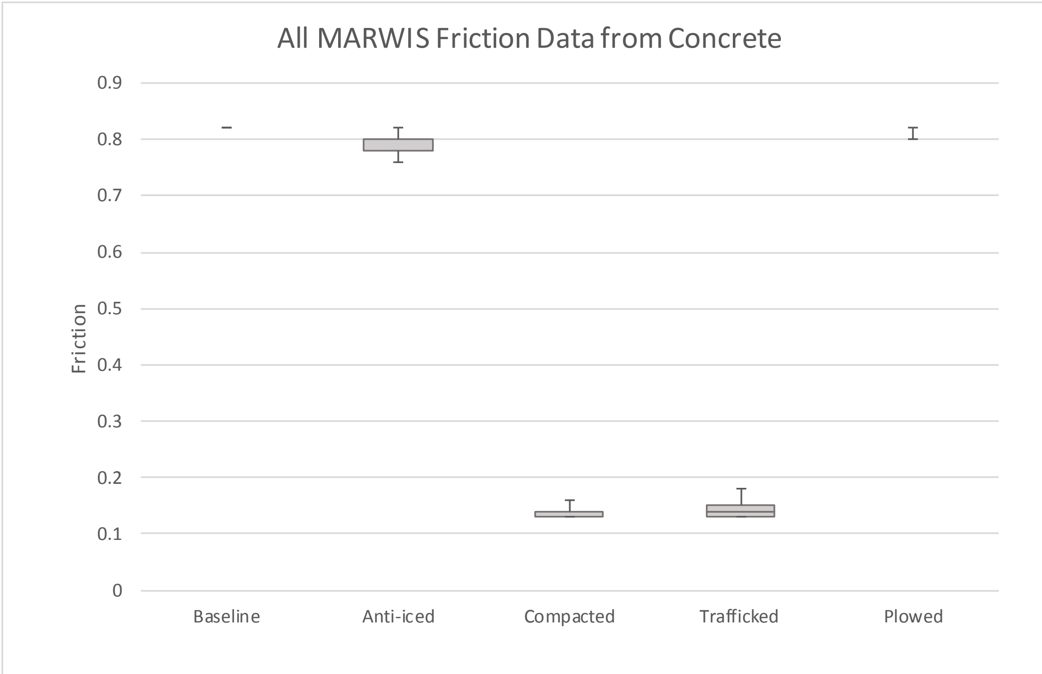


Figure 45. Box plots of all friction data collected by the MARWIS sensor on concrete pavement during snow and trafficking testing

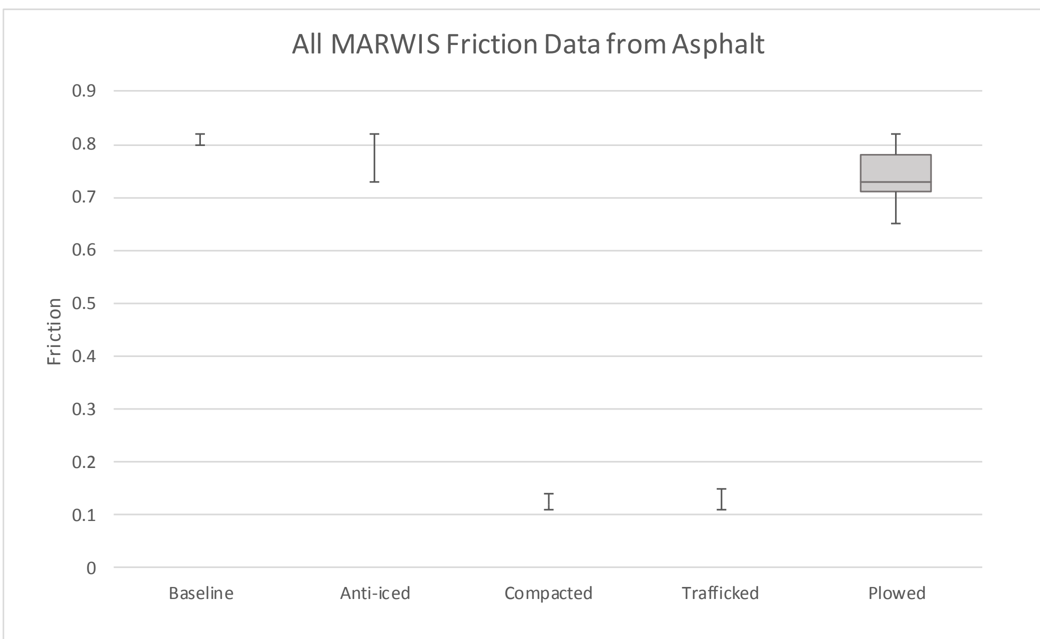


Figure 46. Box plots of all friction data collected by the MARWIS sensor on asphalt pavement during snow and trafficking testing

Figure 47 and Figure 48 show box plots of all friction data collected by the Teconer RCM411 sensor from both asphalt and concrete pavements, respectively. The box plots display higher variability in the friction data recorded during each test condition (e.g., baseline, anti-iced, compacted, trafficked, and plowed/scraped).

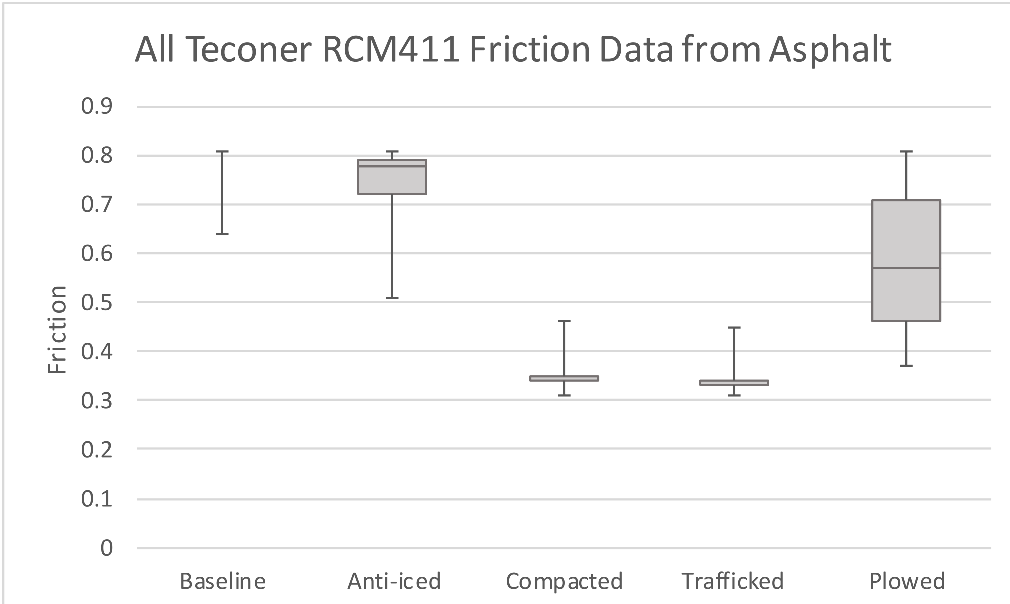


Figure 47. Box plots of all friction data collected by the Teconer RCM411 sensor on asphalt pavement during snow and trafficking testing

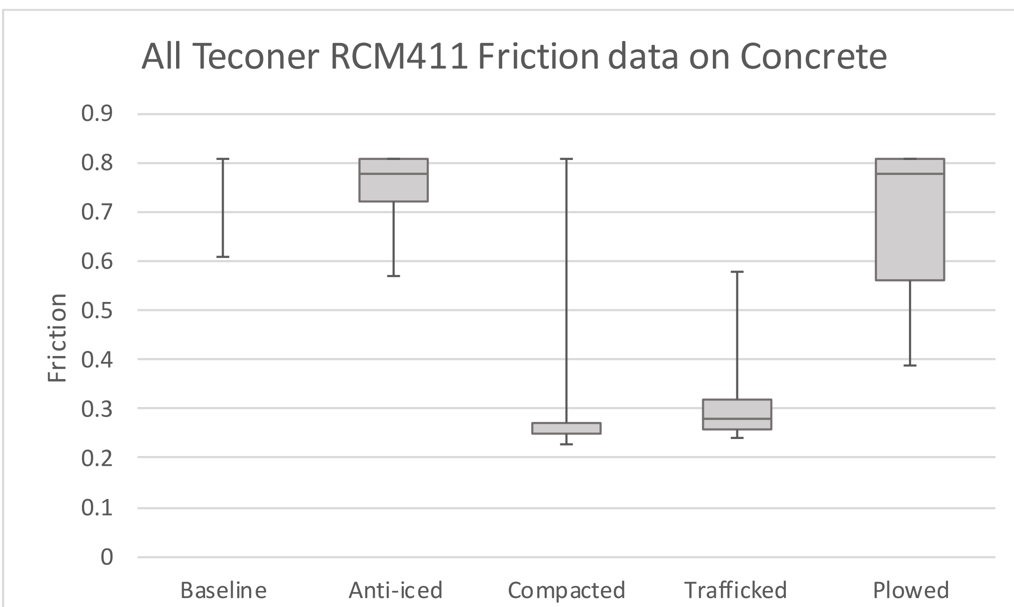


Figure 48. Box plots of all friction data collected by the Teconer RCM411 sensor on concrete pavement during snow and trafficking testing

What can be easily observed from the above box plots (Figure 45 through 48) is the common trend in friction values throughout testing, where friction values start high and remain high following application of anti-icer but the friction decreases to unsafe (slippery) conditions following the application of snow and in subsequent compaction and trafficking. Once the snow is plowed/scraped off the pavement surface, the friction values increase to moderate to safe conditions. Friction data from both the Teconer RCM411 and MARWIS sensors accurately detect changes in pavement friction over the course of laboratory testing.

Pavement Surface Temperature

The MARWIS and Teconer RCM411 sensors both recorded pavement temperature data during snow and trafficking testing. A review of the data collected is provided below.

As can been seen in Table 7, the pavement temperatures reported by the Teconer RCM411 on average are very similar to the actual room temperature of 28°F.

Table 7. Pavement surface readings from the Teconer RCM411

Test Date	Sample Type Concrete/Asphalt (C/A)	Pavement Temperature (°F)	
		Average	Standard Deviation
7/3	A	26.40	0.67
7/3	C	26.61	0.54
7/5	A	26.66	0.73
7/18	C	27.63	1.34
7/27	C	27.83	1.47
7/31	A	27.62	0.93

*Cold Room air temperature 28.0 ± 0.5 °F.

The variation in the pavement surface temperature data collected by the Teconer RCM411 during snow and trafficking testing can be observed in Figure 49.

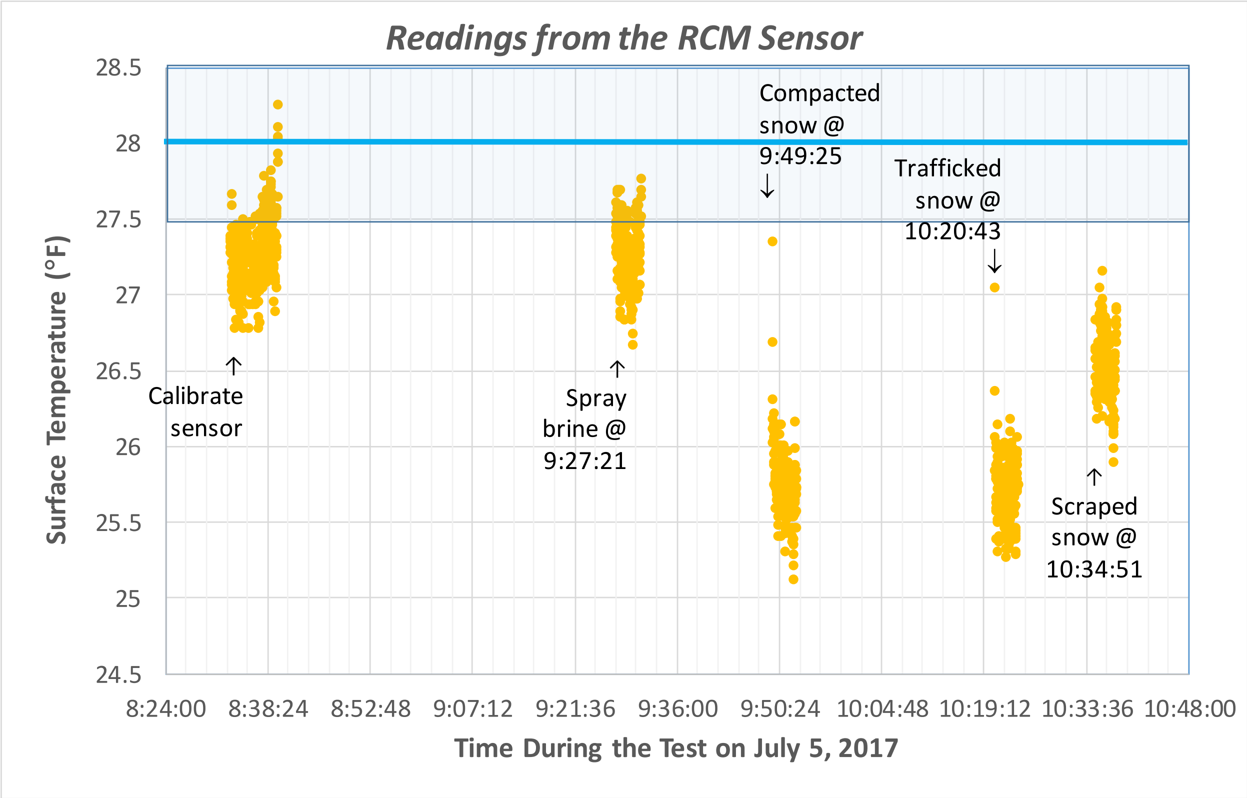


Figure 49. Pavement surface temperature data from the Teconer RCM411, as compared to the Cold Room air temperature of 28 ± 0.5°F (blue line, with error shaded in blue)

The data showed that a decrease or cooling of the pavement surface temperature occurred with the addition of snow and pavement temperatures remained low or grew colder than the air temperature through compaction and trafficking of the snow. Once the snow was plowed/scraped off the pavement sample, the pavement surface temperature increased or warmed, bringing the pavement surface temperature closer to the air temperature. This same trend can be observed in all of the Teconer RECM411 pavement surface temperature data. Additional figures showing pavement surface temperature data from the Teconer RCM411 sensor on both asphalt and concrete pavements can be found in Appendix B.

Figure 50 shows an example of the MARWIS pavement temperature data collected during snow and trafficking testing.

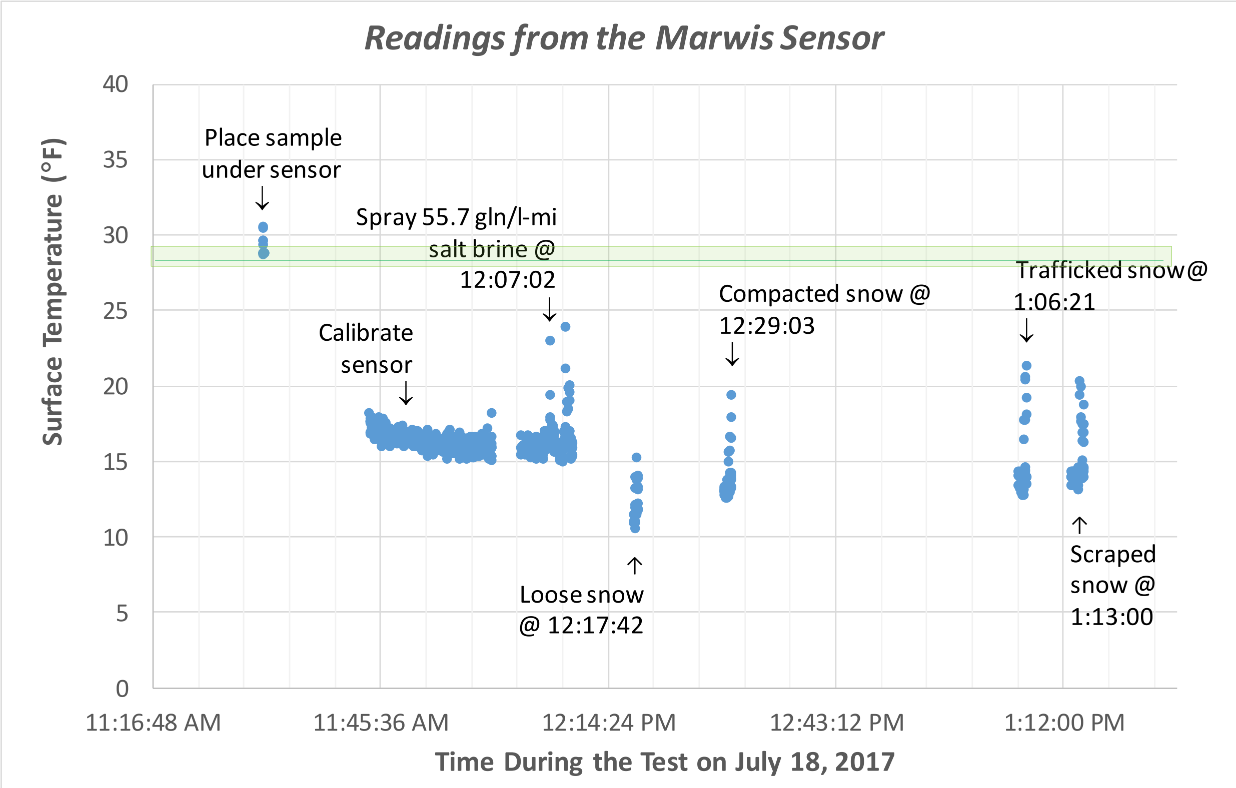


Figure 50. Pavement surface temperature data from the MARWIS sensor, as compared to the cold room air temperature of 28 ± 0.5°F (green line, with the error shaded in green)

As can be observed in period the prior to calibration, the pavement temperature data matches well with the air temperature of 28°F. Following calibration, the data then appears to be off, providing relatively cold pavement temperature data with little variability over the varying test conditions. As can be observed in Table 8, the average pavement surface temperature measured by the MARWIS sensor is significantly different than the air temperature of 28°F.

Table 8. Summary of pavement surface readings from the MARWIS sensor reported by test date and sample type (A = asphalt, C = concrete)

		Pavement Temperature (°F)	
Test Date	**Sample Type**	**Average**	**Standard Deviation**
7/3	A	14.40	1.75
7/3	C	14.13	0.98
7/5	A	14.83	0.96
7/18	C	15.76	1.27
7/27	C	15.48	2.50
7/31	A	15.57	1.62

Additionally, the variability of the data, as observed in the standard deviation from the average, is greater for the MARWIS pavement surface temperature in all tests on both pavement types.

Additional figures showing pavement surface temperature data from the MARWIS sensor on both asphalt and concrete pavements can be found in Appendix B.

The MARWIS sensor has a probe for infrared road temperature measurements but lacks a specific sensor for air temperature. Based on its performance in the laboratory, the MARWIS reporting of road temperatures was highly inaccurate. The vendor was contacted several times about this problem. They offered no specific solution other than "let's see if it continues to be off." It is worth noting that the MARWIS unit used for the testing was a loaner from Lufft and was "refurbished" prior to being used for the testing.

Road Condition Rating

MARWIS

The MARWIS unit reports a derived value called road condition. Definitions of the numeric road condition values of 0 through 9 shown below are from the MARWIS manual (Table 9).

Table 9. Defined road condition ratings provided by the MARWIS sensor

Road Condition Rating	Road Condition description	Notes
0	Dry	No liquid water on the road, water film height is below the "damp" threshold. *The damp threshold is 10 micrometers but can be changed by the user.*
1	Damp	Liquid on the road, water film height is below wet threshold. *The default threshold for wet is 100 micrometers.*
2	Wet	Liquid water on the road, water film height on or above the wet threshold.
3	Ice-covered	Frozen water on the road mainly in the form of ice.
4	Snow/ice-covered	Frozen water on the road either in the form of ice or snow; a more precise differentiation is not possible.
5	Chemically Wet	The water film height is on or above the damp threshold and the road surface temperature is below 1.5°C (34.7°F); the formation of ice is inhibited by the presence of deicing chemicals. *This is non-specific about type of deicer, it just assumes if there is liquid water instead of ice, there must be a chemical present to reduce the freezing point.*
6	Critically Wet	Water film height is on or above the damp threshold and the road surface temperature is below 1.5°C (34.7°F) with the formation of ice particles starting.
7	NA	NA
8	Snow covered	Frozen water on the road mainly in the form of snow.
9	undefined	NA

What can be observed from Figure 51 through Figure 56 is that the road condition rating provided by MARWIS is dynamic and changes on the same frequency as other data reported.

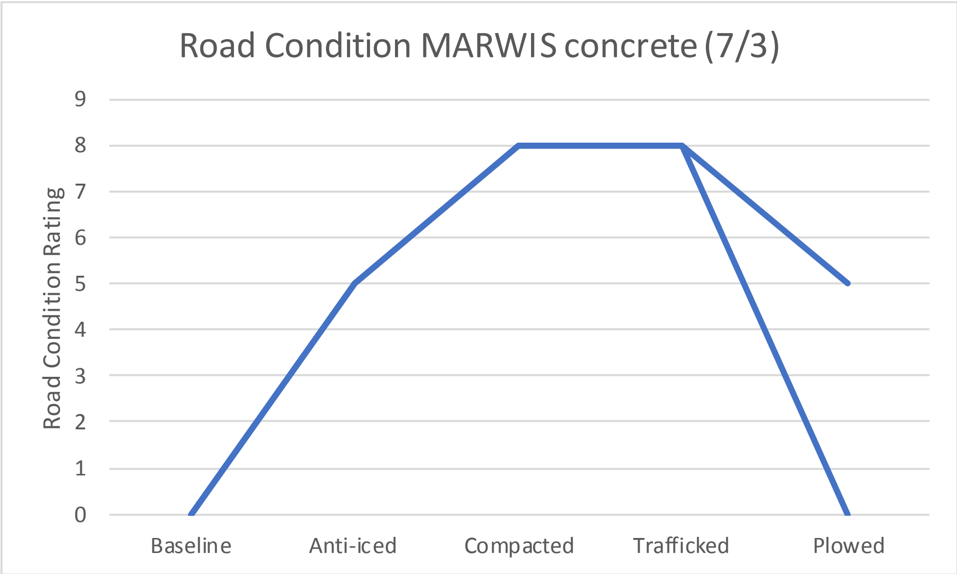


Figure 51. Road condition ratings from the MARWIS unit during testing, concrete 7/3

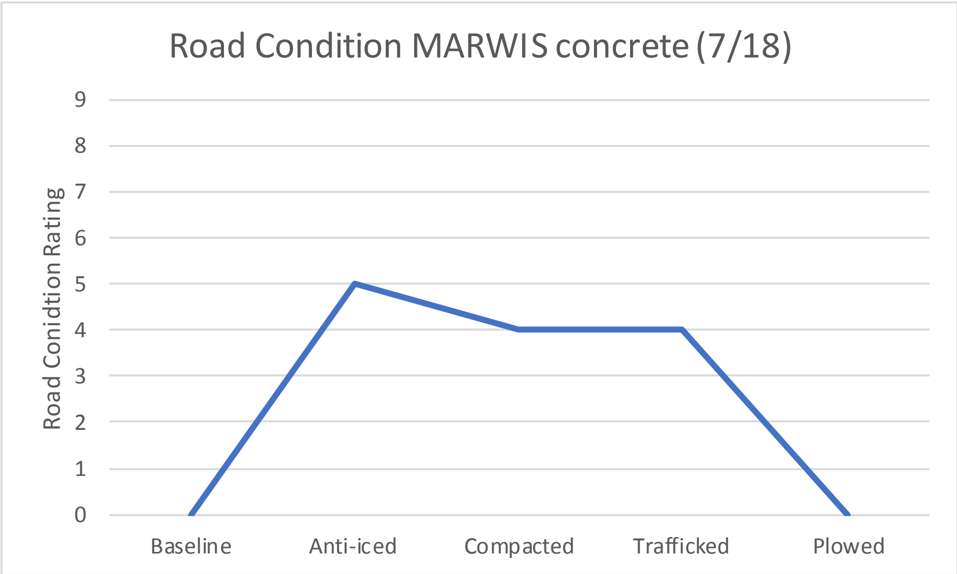


Figure 52. Road condition ratings from the MARWIS unit during testing, concrete 7/18

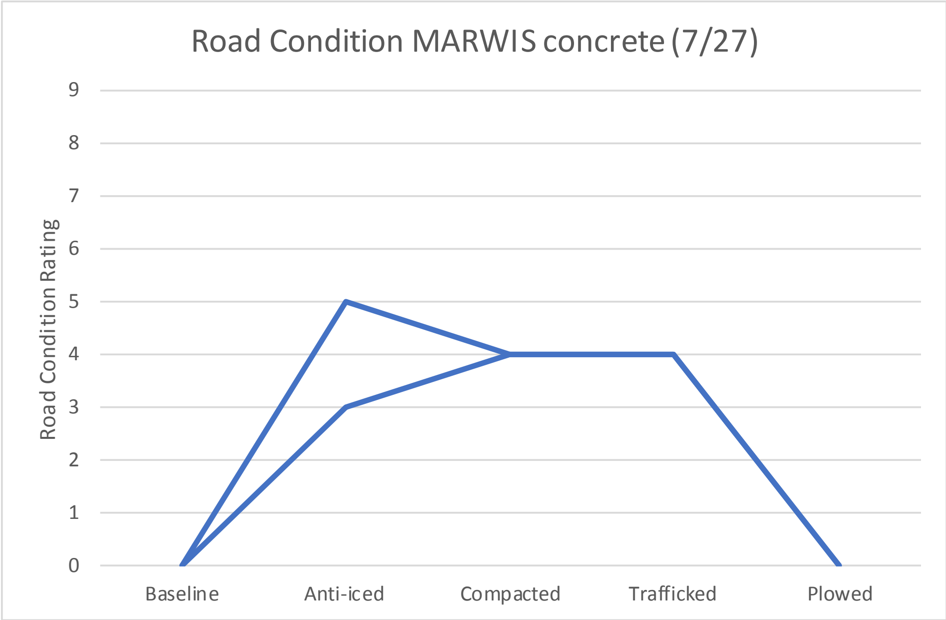


Figure 53. Road condition ratings from the MARWIS unit during testing, concrete 7/27

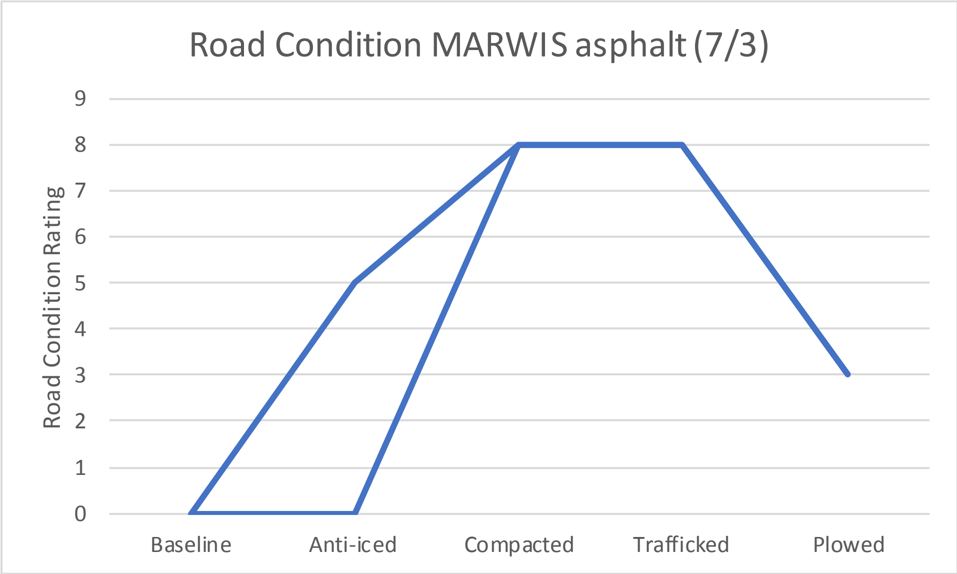


Figure 54. Road condition ratings from the MARWIS unit during testing, asphalt 7/3

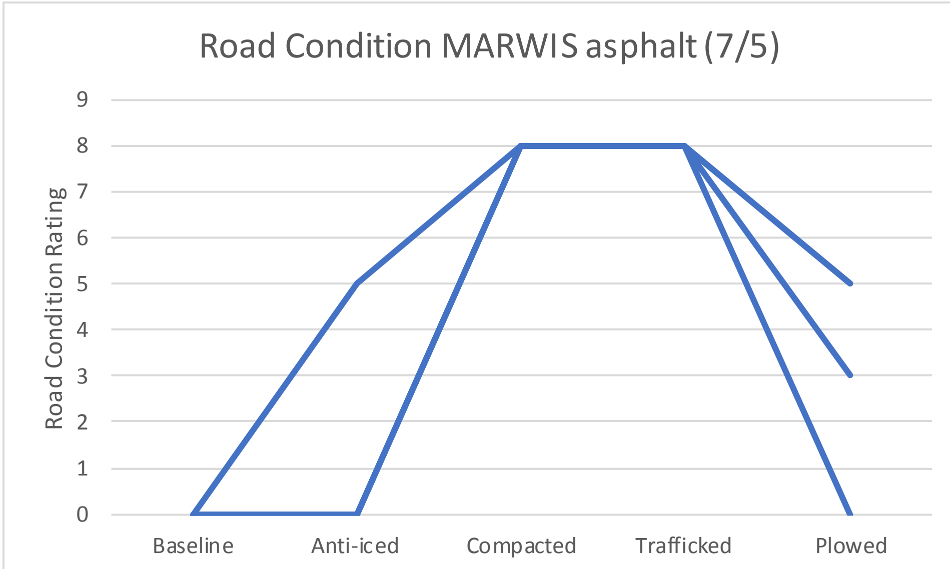


Figure 55. Road condition ratings from the MARWIS unit during testing, asphalt 7/5

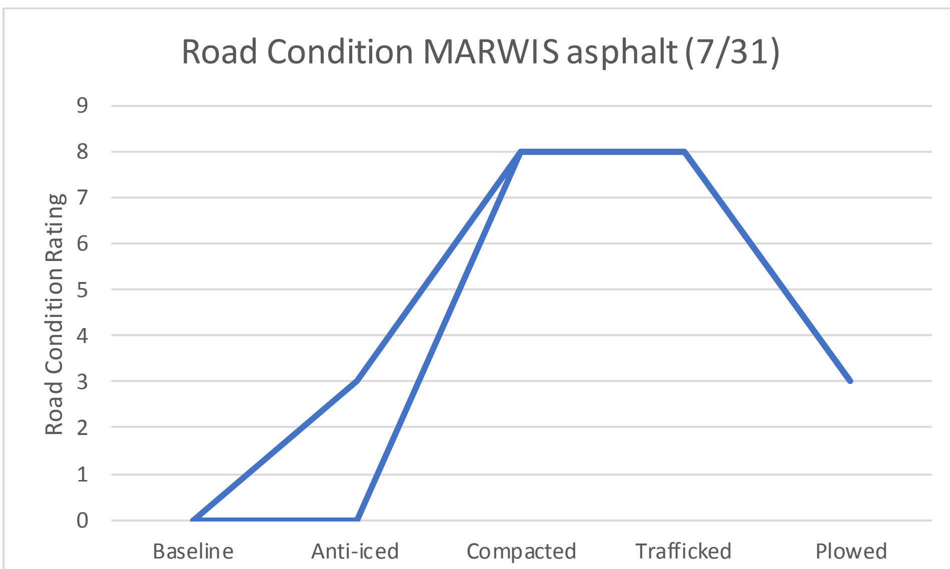


Figure 56. Road condition ratings from the MARWIS unit during testing, asphalt 7/31

Figure 51 shows that at the start of the test, the baseline pavement condition is *dry* (0), when anti-icer is added to the pavement the road condition changes to chemically wet (5), and when snow is added and compacted through trafficking, the road condition changes to snow covered (8). Once the snow is plowed, the MARWIS sensors provide multiple road condition ratings, both chemically wet (5) and dry (0). This shows that the MARWIS sensor is able to quickly detect and report changes in pavement condition spatially and over time.

Note that all road condition ratings for the baseline condition are dry (0). Once the surface is anti-iced, the road condition ratings range from dry (0), to ice-covered (3), to chemically wet (5).

When snow was added, compacted, and trafficked, all road conditions ratings were reported either as snow/ice-covered (4) or snow covered (8). Finally, once the snow was plowed/scraped off the pavement surface, the road condition ratings reported ranged from dry (0), to ice-covered (3), to chemically wet (5), similar to the anti-iced pavement surface.

The road condition data reported from the asphalt pavement samples (Figure 54, Figure 55, and Figure 56) showed more variable ratings than those that were reported from the concrete pavement samples (Figure 51, Figure 52, and Figure 53).

Based on the performance of the road condition rating feature developed by MARWIS, it is safe to say this a dynamic tool that can be used to determine the road condition remotely. Note that the MARWIS road condition rating has a value for critically wet (6) defined as: “The water film height is on or above the damp threshold and the road surface temperature is below 1.5°C (34.7°F); the formation of ice is inhibited by the presence of deicing chemicals.” Testing for this study occurred at 28°F, well within the functional temperature range for the salt brine (NaCl, liquid) anti-icer that was used. At no point in this testing was the critically wet (6) category reported, showing that for salt brine the MARWIS road condition rating tool functioned well.

Teconer RCM411

The Teconer RCM411 derives a surface state value reported to a road condition map. On the user interface, the road condition map shows surface states as colors along the roads being monitored, but the data are provided as numeric values, which are defined in Table 10.

Table 10. Defined surface state as the color reported on the road condition map, and numeric values provided in the data by the Teconer RCM411

Surface State Rating	Surface State Color	Road Condition	Notes
1	Green	Dry	
2	Light Blue	Moist	
3	Dark Blue	Wet	
4	Violet	Slushy	Ice or snow with water.
5	Red	Ice	
6	White	Snow	

What can be observed from Figure 57 through Figure 62 is that the surface state rating provided by Teconer RCM411 is dynamic and changes on the same frequency as other data reported.

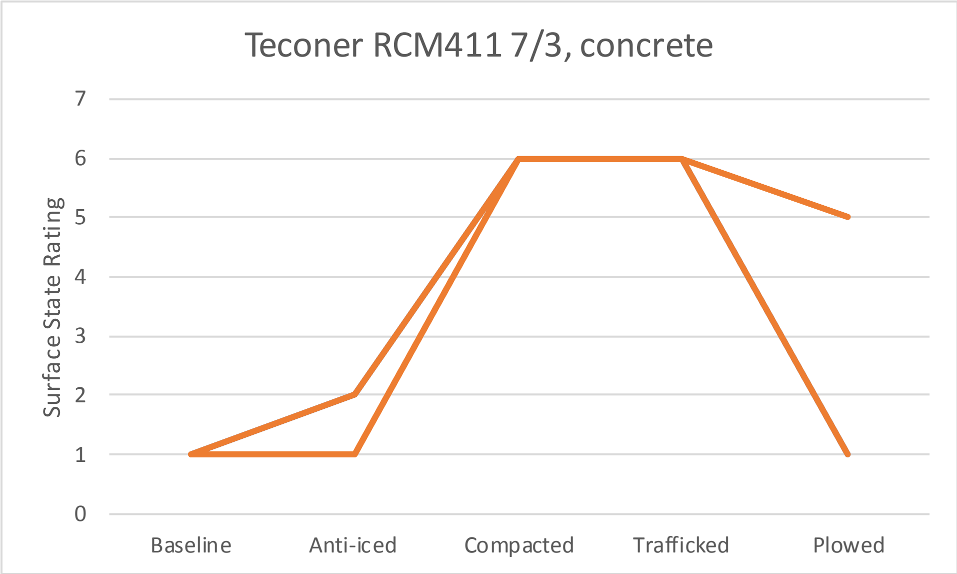


Figure 57. Surface state rating from the Teconer RCM411 sensor during testing, concrete 7/3

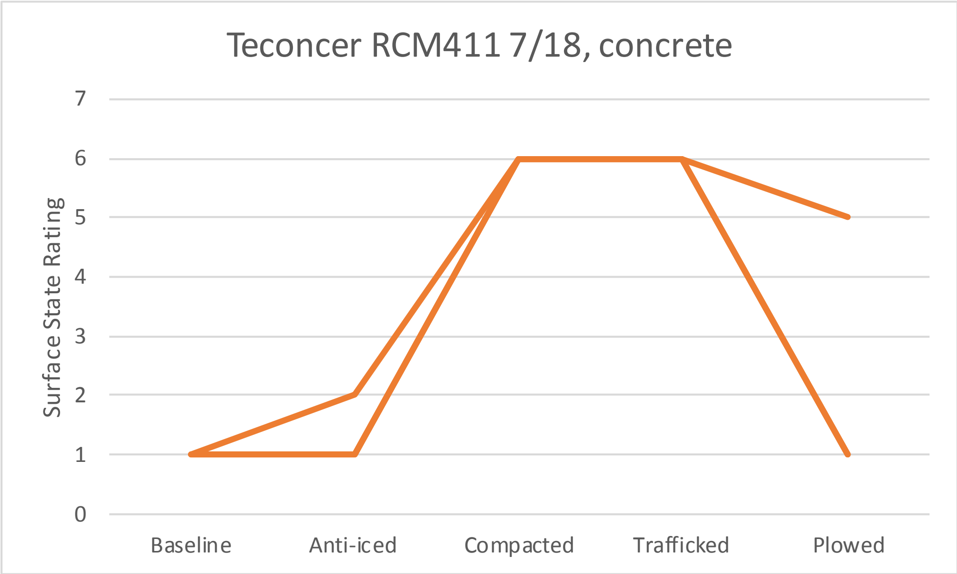


Figure 58. Surface state rating from the Teconer RCM411 sensor during testing, concrete 7/18

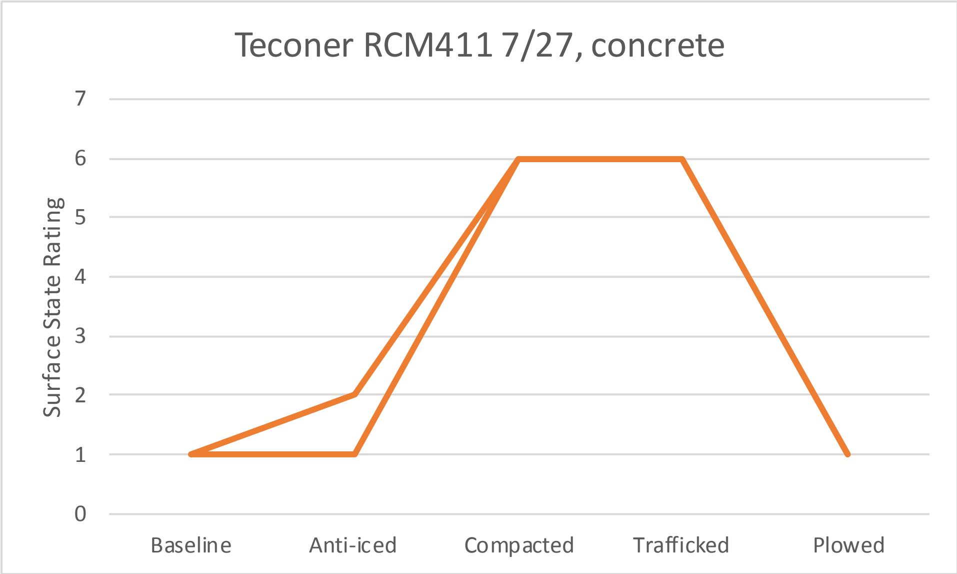


Figure 59. Surface state rating from the Teconer RCM411 sensor during testing, concrete 7/27

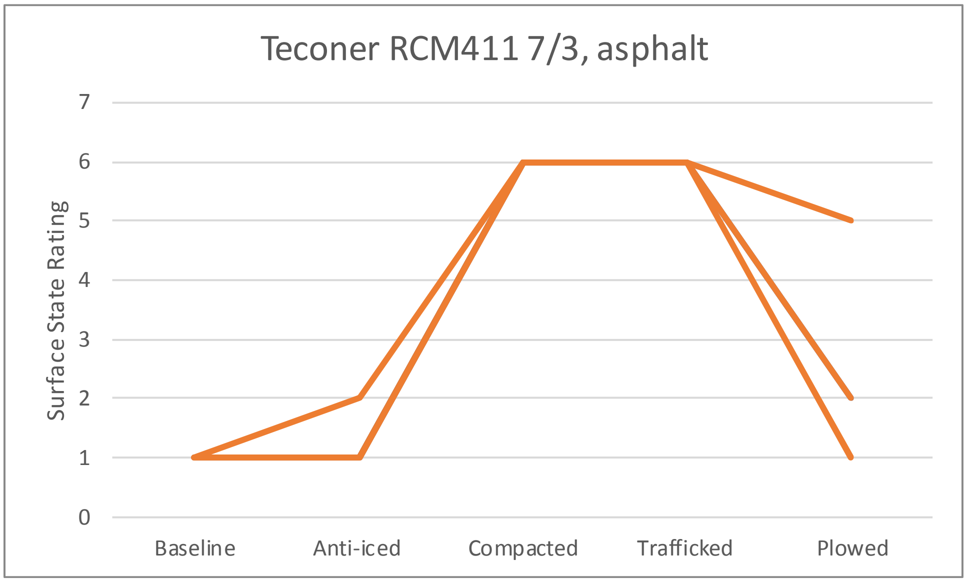


Figure 60. Surface state rating from the Teconer RCM411 sensor during testing, asphalt 7/3

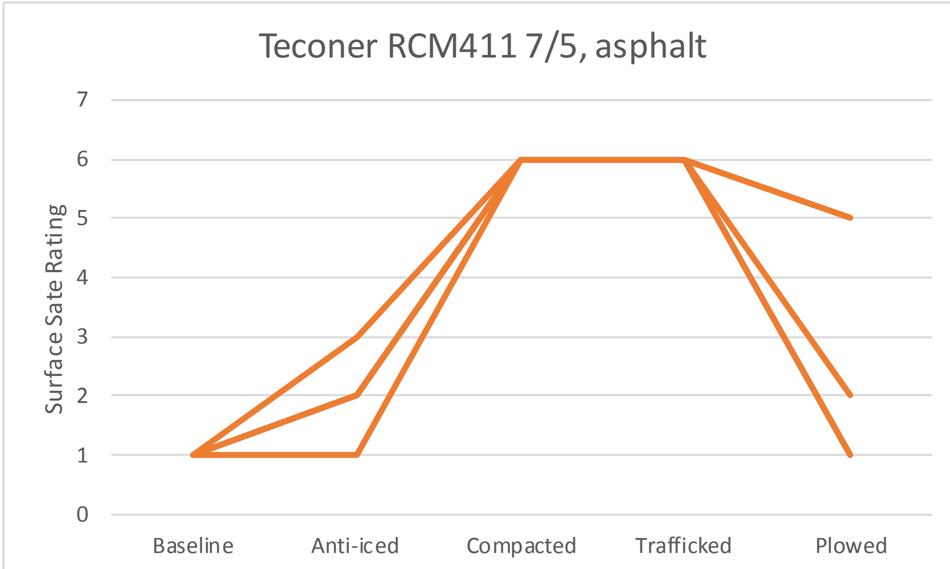


Figure 61. Surface state rating from the Teconer RCM411 sensor during testing, asphalt 7/5

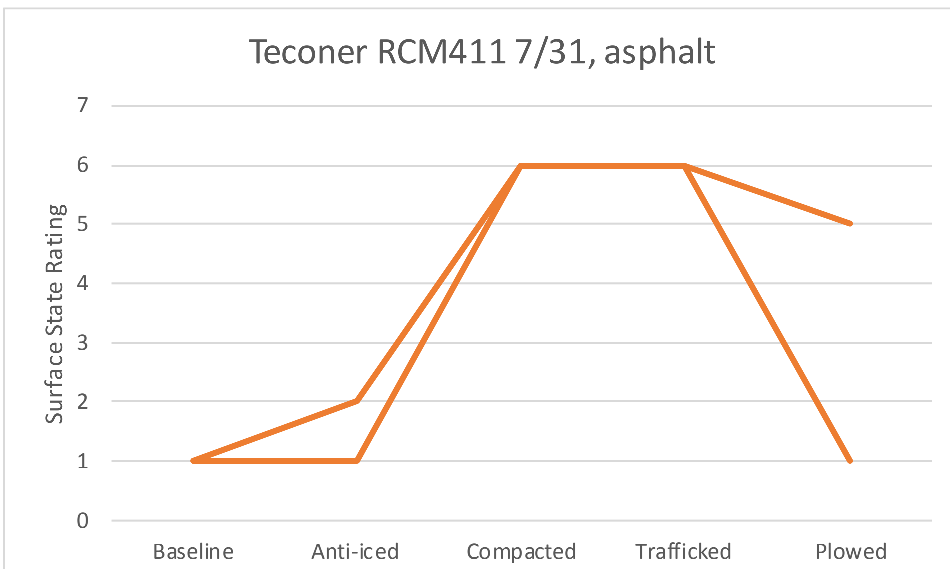


Figure 62. Surface state rating from the Teconer RCM411 sensor during testing, asphalt 7/31

For this reason, as shown in Figure 57, at the start of the test the baseline pavement condition is dry (1), and when anti-icer is added to the pavement, the road condition is reported both as dry (1) or changed to moist (2). When snow was added and compacted through trafficking, the surface state rating changed to snowy (6). Once the snow is plowed off, the RCM411 sensors provided multiple surface state ratings, both icy (5) and dry (1). This shows that the Teconer RCM411 sensor is able to quickly detect and report changes in pavement conditions spatially and over time.

Note that all surface state ratings for the baseline condition are dry (1). Once the surface is anti-iced, the surface state ratings ranged from dry (1), to moist (2), to wet (3). When snow was added, compacted, and trafficked, all surface state ratings were reported as snowy (6). Finally, once the snow was plowed/scraped off the pavement surface, the surface state ratings reported ranged from dry (1), to moist (2), to icy (5).

The surface state data reported from the asphalt pavement samples (Figure 60, Figure 61, and Figure 62) showed more variability in the ratings that were reported than those taken from the concrete pavement samples (Figure 57, Figure 58, and Figure 59).

Based on the performance of the surface state rating feature developed by Teconer RCM411, it is safe to say that this a dynamic tool that can be used to determine the road condition remotely.

MARWIS Ice Percent on the Pavement Surface

As noted in the section on water/ice depth testing, the MARWIS sensors measure percent ice (%) on the pavement surface. Percent ice data collected during the snow and trafficking testing are shown below in Figure 63 and Figure 64 for concrete and asphalt pavements, respectively.

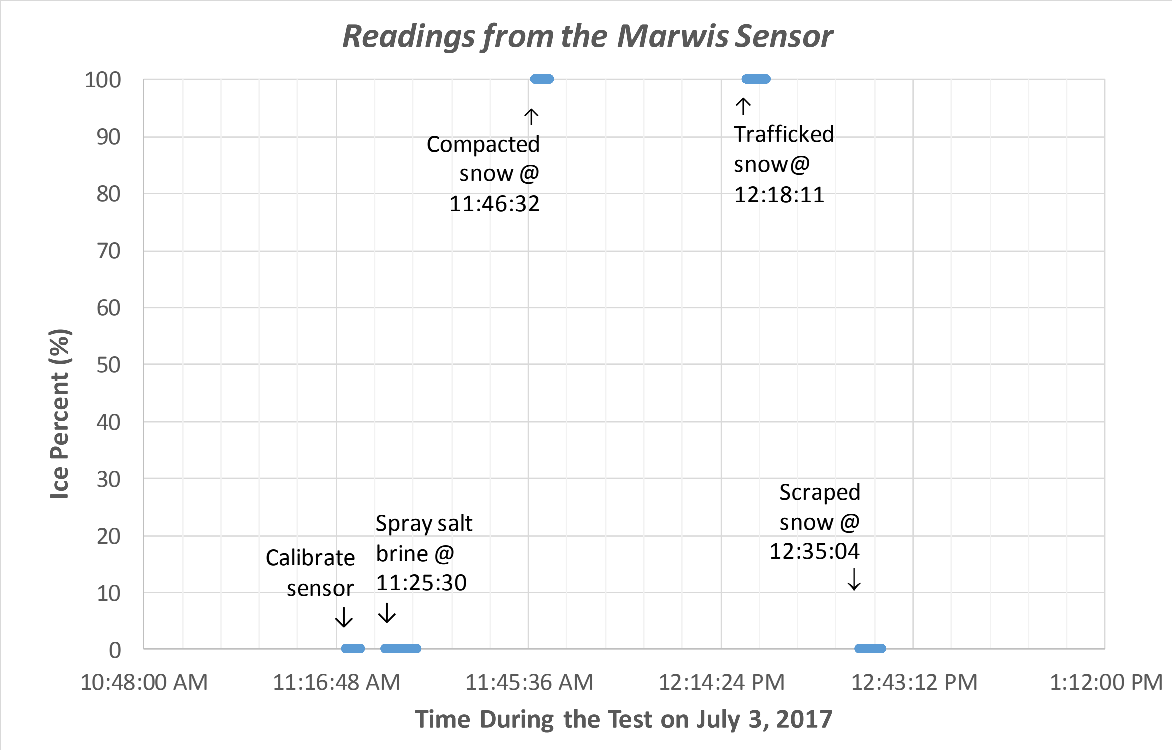


Figure 63. Percent ice detected on the pavement surface by the MARWIS sensor on concrete pavement

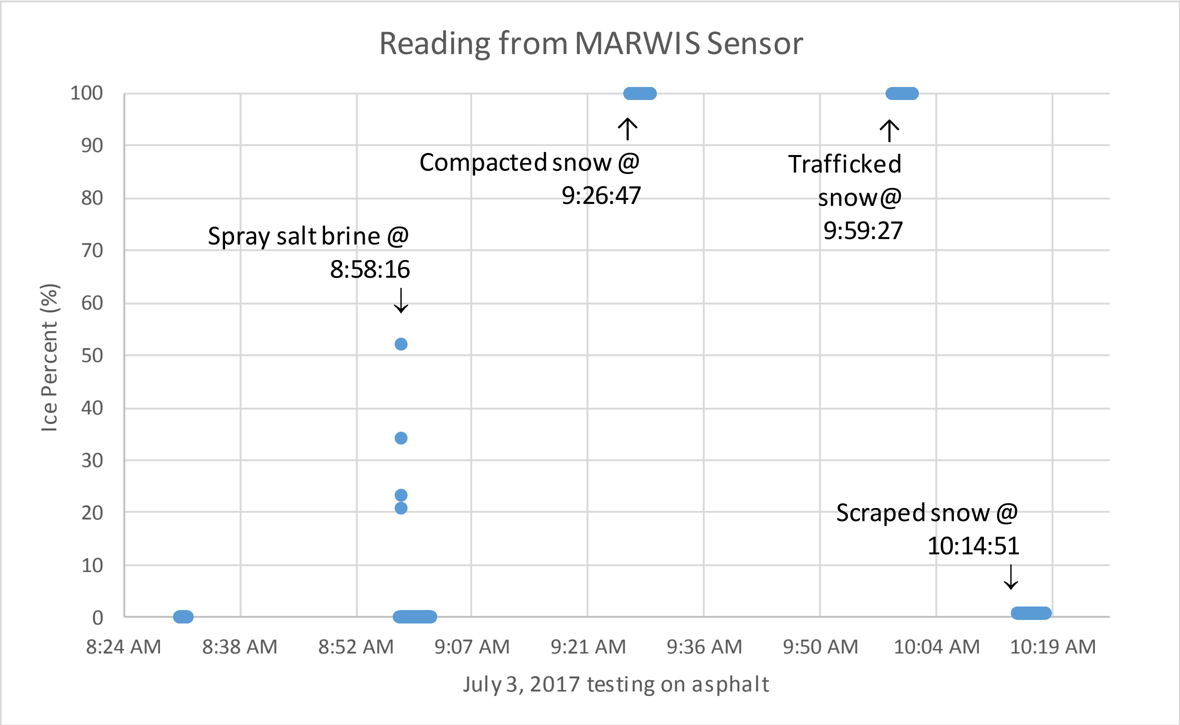


Figure 64. Percent ice detected on the pavement surface by the MARWIS sensor on asphalt pavement

The ice percent data shown below are a typical representation of all of the data collected during snow and trafficking testing. As noted, ice percent was zero at the time of calibration. For some (but not all) samples, percent ice values increased as the anti-icer was detected on the pavement surface. For all samples, the addition of snow through compaction and trafficking, the ice percent values were 100%. Once the snow was plowed/scraped off the pavement surface, ice percent values generally went back to zero, but not for all samples. Following application of the anti-icer and plowing/scraping of snow, the ice percent data were variable only for some of the samples. There were no consistent trends or identified inconsistencies between concrete or asphalt pavement samples. Additional figures showing ice percent from the MARWIS sensor on both concrete and asphalt pavement can be found in Appendix B.

Chloride Concentration in Plowed/Scraped off Snow

During the snow and trafficking testing, the snow that was plowed/scraped off the pavement surface was collected for further testing. The chloride concentration of the snow was measured to determine the amount of chloride removed from the pavement surface and the amount remaining on the pavement surface. Table 11 provides a summary of the type of pavement sample, the measured application rate of the salt brine applied, and the measured chloride concentration of the snow that was plowed/scraped off the trafficked sample.

Table 11. Summary sample type, salt brine application rate, and measured chloride concentration from the snow plowed off the trafficked samples

Pavement Type (C=concrete or A-asphalt)	Salt Brine App. Rate (gal/LM)	Measured Chloride Concentration (mg/L)	Percent of Chloride in the Plowed-Off Snow (%)	Percent of Chloride Remaining on the Pavement (%)
A	36.1	406	54.4	45.6
A	59.5	1,110	87.9	12.1
A	47.8	865	85.2	14.8
C	55.7	141	11.6	88.4
C	27.9	14.3	2.4	97.6
C	39.3	187	21.9	78.1

Note: The boxes in highlighted gray are the calculated percent chloride in the plowed-off snow and percent chloride remaining on the pavement surface. All testing was conducted at 28°F.

The general trends that can be observed are the higher concentrations of chloride in the plowed-off snow from the asphalt samples (54%, 88%, and 85%), and, therefore, lower concentrations of chloride remaining on the asphalt pavement surface (46%, 12%, and 15%). In contrast, the concrete samples showed lower concentrations of chloride in the plowed-off snow (12%, 2%, and 22%), and, therefore, higher concentrations of chloride remaining on the pavement surface (88%, 98%, 78%). This trend had not been observed in previous testing, and additional work is recommended to confirm this trend. Work by Hunt et al. (2004) identified the factors affecting residual concentrations on the pavement as application method, pavement porosity, and surface roughness.

Additionally, the percentages of chlorides remaining on the pavement surfaces (12% to 45% for asphalt and 78% to 98% for concrete) represent a wide range of residual chloride on the pavement. For this reason, it is not yet feasible to make recommendations for changing subsequent deicer application rates based on pavement surface type (asphalt versus concrete).

Past work by Muthumani et al. (2015) found similar rates of chloride removal with trafficking and plowing/scraping of snow from asphalt pavement. At 5°F, they observed 80% to 90% removal of chlorides from trafficking and plowing, and at 15°F, they observed 45% to 80% removal of chlorides from trafficking and plowing (Figure 65).

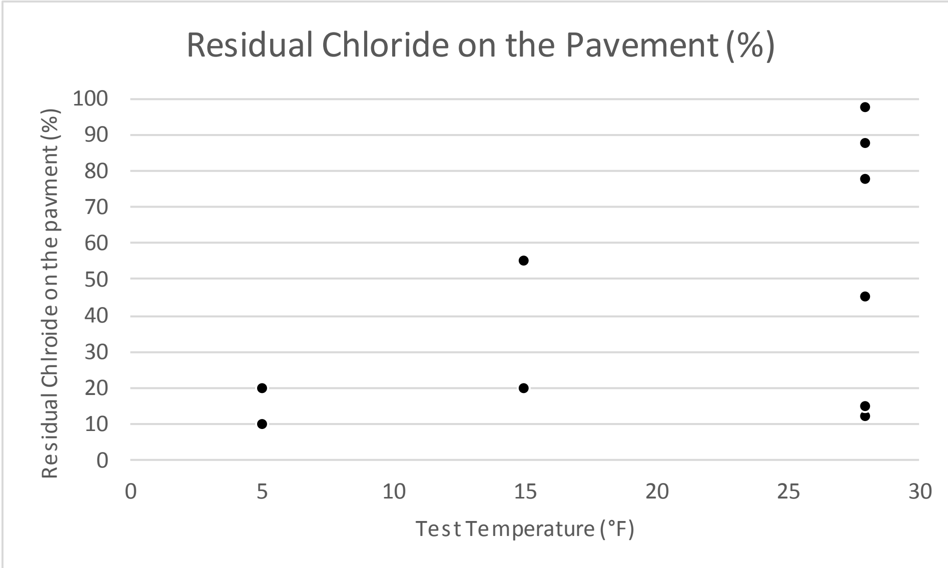


Figure 65. Range of residual chloride remaining on the pavement surface (as %) after anti-icing, addition of snow and compaction, trafficking, and plowing from this research effort (28°F on asphalt (A) and concrete (C) pavements) and from research by Muthumani et al. (2015) (5°F and 15°F) on asphalt (A) pavement

The data from Muthumani et al. (2015) show a decrease in chloride removal with warmer temperatures. This could explain the lower chloride removal rates with plowing at the 28°F testing level, but additional testing is recommended to confirm this trend.

The residual 12% to 97% of chloride that remains on the pavement surface should facilitate anti-icing during a subsequent storm event, specifically on concrete pavement samples where the remaining percentages of chloride are higher. The remaining chloride on the pavement should be sufficient to allow for chemically wet readings measured by mobile non-invasive pavement surface sensors. Additional testing is suggested to confirm this. With more testing and more consistent data, it may also be feasible to determine a subsequent reduced deicer application rate and collect a more robust dataset on residual chloride remaining on the pavement surface. In addition, it is unknown how much chloride was lost in trafficking tests on the sample, snow removal from the pavement surface, and sample processing. More testing that closely tracks chloride applied and chloride lost during testing will likely provide more accurate data on residual chloride

CONCLUSIONS

The objective of this project was to evaluate the Lufft MARWIS and Teconer RCM411 sensors' ability to perform in a typical winter maintenance environment as was simulated in a laboratory setting, investigate the sensors' sensitivity to varying chloride concentrations, assess the repeatability of data and the sensors' mechanical reliability, and evaluate each sensor's state of development and cost to purchase, install, and maintain.

Within the laboratory testing, the objective was to simulate real world conditions of snow, ice, and/or slush on pavement, trafficking, and plowing and assess how each sensor performed with the addition of each of these variables and detected the change in pavement condition/deicer performance throughout winter maintenance operations. For the MARWIS sensor, water/ice depth, ice percent, friction, pavement surface temperature, and road condition rating were evaluated. For the Teconer RCM411 sensor, water depth, friction, pavement surface temperature, and surface state rating were evaluated.

A summary of the findings is provided below.

- **Water/ice depth** – The Teconer RCM411 sensor fairly accurately detects the addition of liquid to the pavement surface when it is first added and captures the phenomenon of the water freezing over time (i.e., the water depth decreasing). The sensor could not detect the first addition of water at very cold temperatures (-20°F) due to the rapid freezing of water. The three sensing elements from the RCM411 sensor were capable of detecting the change in pavement surface conditions reliably under this investigated scenario. But, due to the sensitivity of the sensor, the data were highly variable when water was detected by the RCM411 sensor. The MARWIS sensor appeared to be sensitive at detecting the changes in the water/ice depth and detected all applications of water regardless of air and pavement temperatures. Overall, the water/ice depth data reported by the MARWIS were very precise and tightly clustered (i.e., less variable), but it is unknown if the data were more accurate. For both sensors, the response time was almost immediate (0 to 4 seconds) for data reporting, and the sensors detected greater water depth on the concrete samples than on the asphalt samples.
- **Friction** - Friction data from both the Teconer RCM411 and MARWIS sensors accurately showed changes in pavement friction over the course of laboratory testing. The common trend in friction values throughout testing was that friction started high and remained high following application of the anti-icer, but friction values decreased to unsafe (slippery) conditions following the application of snow, and subsequent compaction and trafficking. Once the snow was plowed/scraped off the pavement surface, the friction values increased to moderate levels to create safer pavement conditions. Changes in friction were reported by the sensors almost instantaneously (as each new data point was recorded, within seconds), but it took upwards of 70 seconds for the data to stabilize during testing. This does not appear to be a fault or error in the data, instead the sensors appeared to be observing the change in friction as the pavement condition changed, with the variability arising due to the sensitivity of the sensors.
- **Pavement Surface Temperature** – The Teconer RCM411 recorded pavement surface temperature within 1 degree of the room temperature before snow was placed on the

pavement surface. Once snow was added through compaction and trafficking, the pavement temperature grew significantly colder by 1°F to 2°F. The pavement temperature warmed back to the room temperature once the snow was plowed/scraped off. In contrast, the pavement surface temperature data from the MARWIS was not accurate, recording temperatures 10°F to 15°F colder than the room temperature. Efforts were made to work with Lufft to generate more accurate pavement surface temperature data, but the issue was not resolved prior to the end of testing. Interestingly, the MARWIS pavement temperature data appear to be the only data that were "off," suggesting that maybe this sensor's element needed to be replaced.

- **Road Condition and Surface State** - Based on the performance of the road condition rating (MARWIS) and surface state rating (Teconer RCM411) features, it is safe to say that both sensors offer a dynamic tool that can be used to determine the road condition remotely. For both sensors, the derived road condition and surface state ratings, by MARWIS and the RCM411, respectively, were more variable when collected from asphalt pavement than from concrete.
- **Ice Percent (MARWIS only)** – The data from the snow and trafficking testing showed that the ice percent data from the MARWIS sensor were fairly consistent. The only variable data appeared when the sensors detected the anti-icer frozen as ice on the pavement surface and when the snow was plowed/scraped off the pavement sample, likely creating a more variable surface condition.
- **Chloride concentration in the plowed snow** – Under the investigated scenarios, the asphalt samples showed higher concentrations of chloride in the plowed-off snow, and therefore lower concentrations of chlorides remained on the pavement surface. In comparison, the concrete samples had much lower chloride concentrations in the plowed-off snow, and much higher chloride concentrations remained on the pavement surface. Another interesting pattern revealed by the testing was the variation in the percentage of residual chloride remaining on the pavement surface with changes in temperature. When pavement type was not considered, more residual chloride appeared to be present at warmer temperatures, and less residual chloride was present at colder temperatures. This observation warrants additional testing to determine if this pattern is in fact a statistically valid trend.

At first glance, the results of this effort may to be a comparison between the MARWIS and Teconer RCM411 sensors. The reality is that this research evaluated the performance of each sensor as a standalone unit under a controlled laboratory simulation of the field environment. It is important to note that the testing conditions were ideal in that they were consistent and reproducible. But, from a field use perspective, the air and pavement temperatures were at relatively "warm" winter conditions (28°F) for the bulk of the testing, and the sensors were not exposed to harsh field environments with splash, spray, and debris from the road affecting the sensors and the readings. There were some issues with the sensors' performance at the colder -20°F testing temperature. Additional issues with the equipment not functioning at the colder temperature precluded snow and trafficking testing at -20°F. Because the majority of testing was conducted at the warmer 28°F level, the conclusions from this effort should be applied with caution. Given the conservative and mild nature of the testing, it is likely other issues or sensor values that could occur in the field were not observed in the laboratory.

For example, one issue the research effort cannot provide input on relates to the frequency and methods for cleaning the sensors to ensure quality data. A number of deviations and issues were encountered in the laboratory testing and are discussed as follows.

At temperatures below 5°F, MARWIS needed a 15-volt power supply because the supplied 12-volt was not sufficient. Additionally, the MARWIS provided communications within a minute, but a status light provided a cold-temperature warning for several minutes during a “warm up” period before indicating it was ready. The duration of the “warm up” period for MARWIS varied with temperature; at 25°F warm up was about 10 minutes, but at -20°F warm up took about 60 to 90 minutes. If the sensors were mounted on vehicles stored in garages, the warm-up period would conceivably be shorter.

With MARWIS, when calibration was conducted on concrete pavement it would accurately report dry pavement conditions for concrete, then asphalt, then concrete when swapping the pavement samples. However, when it was calibrated on asphalt pavement, it would often inaccurately report concrete pavement as “chemically wet” when it should have shown “dry.” In comparison, the RCM411 more accurately reported dry pavement regardless of whether calibration occurred on asphalt or concrete samples, except during longer breaks between tests.

An interesting result found by both sensors was the increased variability of reported data from asphalt versus concrete pavement samples. Due to the consistency in increased variability of data from both sensors and the identified need for calibration on each pavement type, which was conducted prior to each test, the researchers feel the increased variability of data from asphalt pavement is not an error in the data being reported but is instead an artifact of the data being collected from asphalt pavement. Additional research is recommended to determine if readings from all asphalt pavements vary as much as the data collected in this research effort. Likewise, it should be further considered whether readings from all concrete pavements are as consistent as the data collected by both sensors in this research effort.

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Muthumani, A., L. Fay, D. Bergner, and X. Shi. 2015. *Understanding the Effectiveness of Non-Chloride Liquid Agricultural By-Products and Solid Complex Chloride/Mineral Products*. Clear Roads and Minnesota Department of Transportation, St. Paul, MN. http://clearroads.org/project/13-02/.

APPENDIX A. WATER/ICE DEPTH TESTING, ADDITIONAL FIGURES

Water/Ice Depth

Teconor RCM411

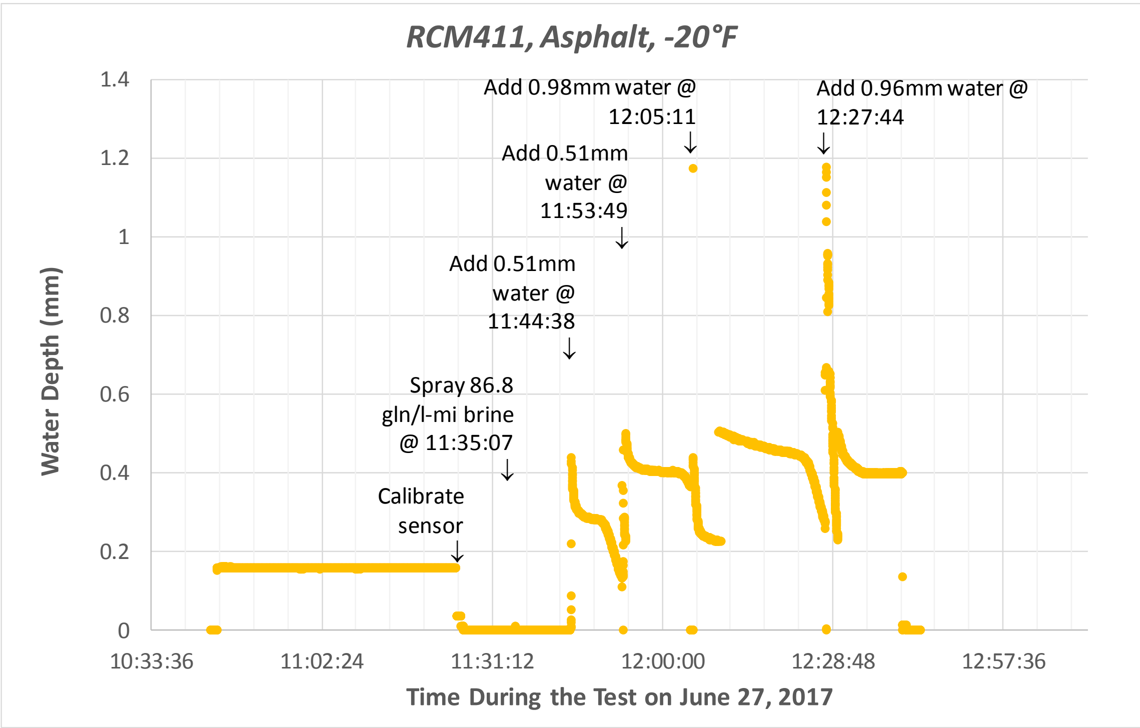


Figure 66. Water depth data reported by the Teconer RCM411 at calibrations, after anti-icing, and application of water four times (0.51 mm, 0.51 mm, 0.98 mm, and 0.96 mm), with data collected from an asphalt sample at an air and pavement temperature of -20°F

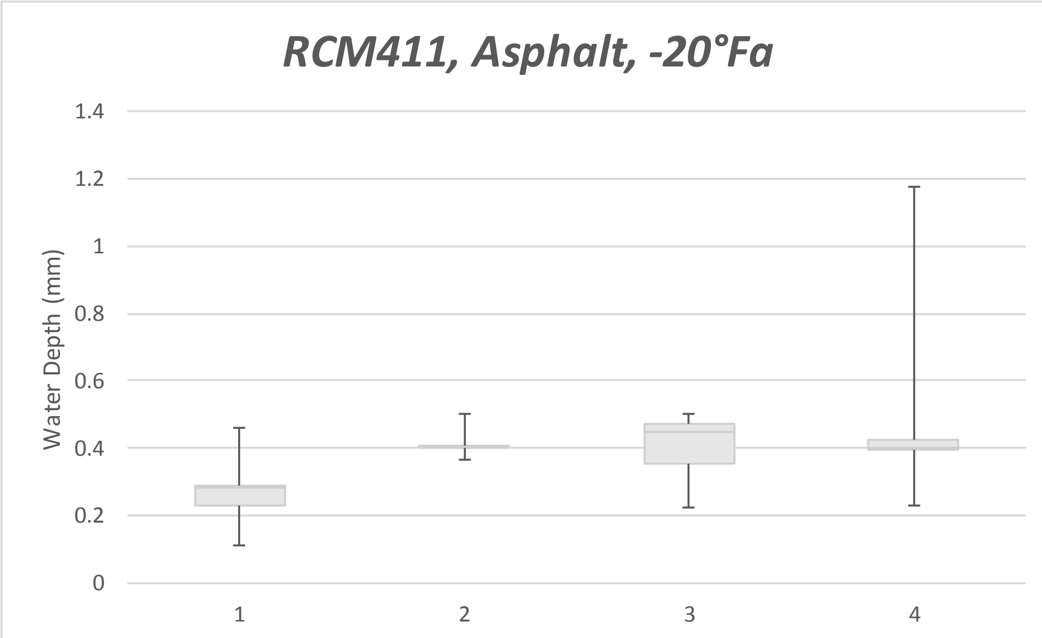


Figure 67. Box plot of the water/ice depth data measured by the Teconer RCM411 sensor on asphalt (a) at -20°F

MARWIS

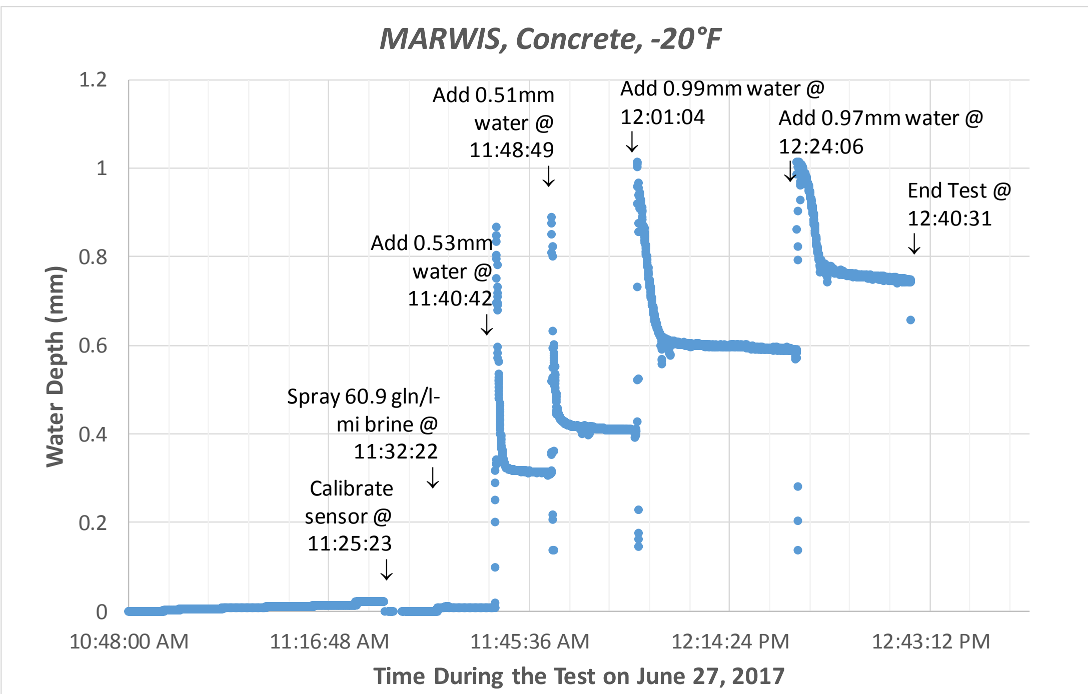


Figure 68. Water depth data reported by the MARWIS at calibration, after anti-icing, and application of water four times (0.53 mm, 0.51 mm, 0.99 mm, and 0.97 mm), with data collected from a concrete sample at an air and pavement temperature of -20°F

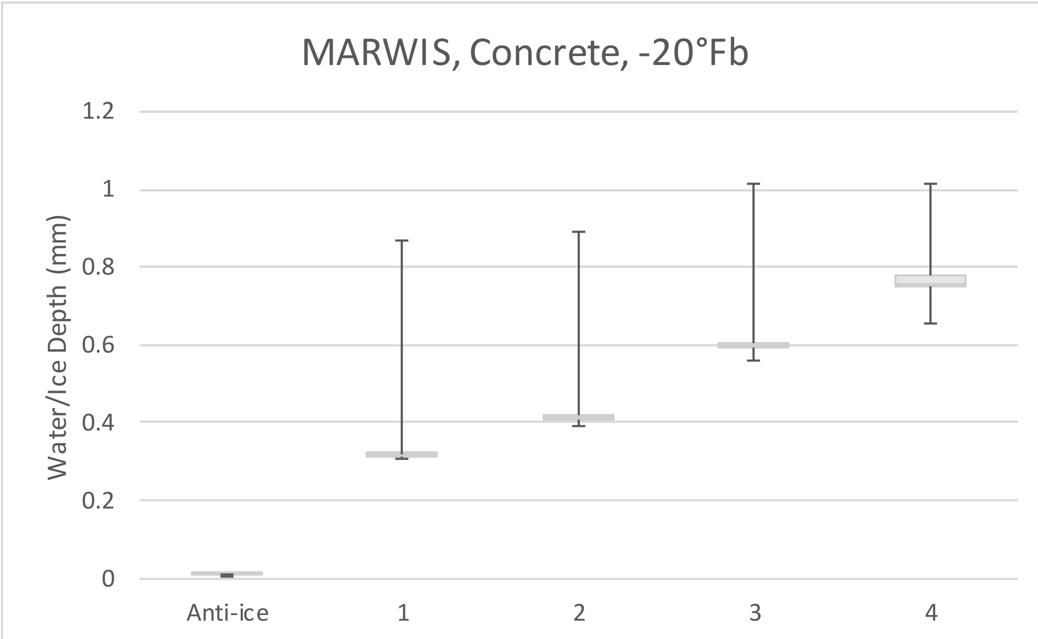


Figure 69. Box plot of the water/ice depth data measured by the MARWIS sensor on concrete (b) at -20°F

MARWIS - Ice Percent Figures

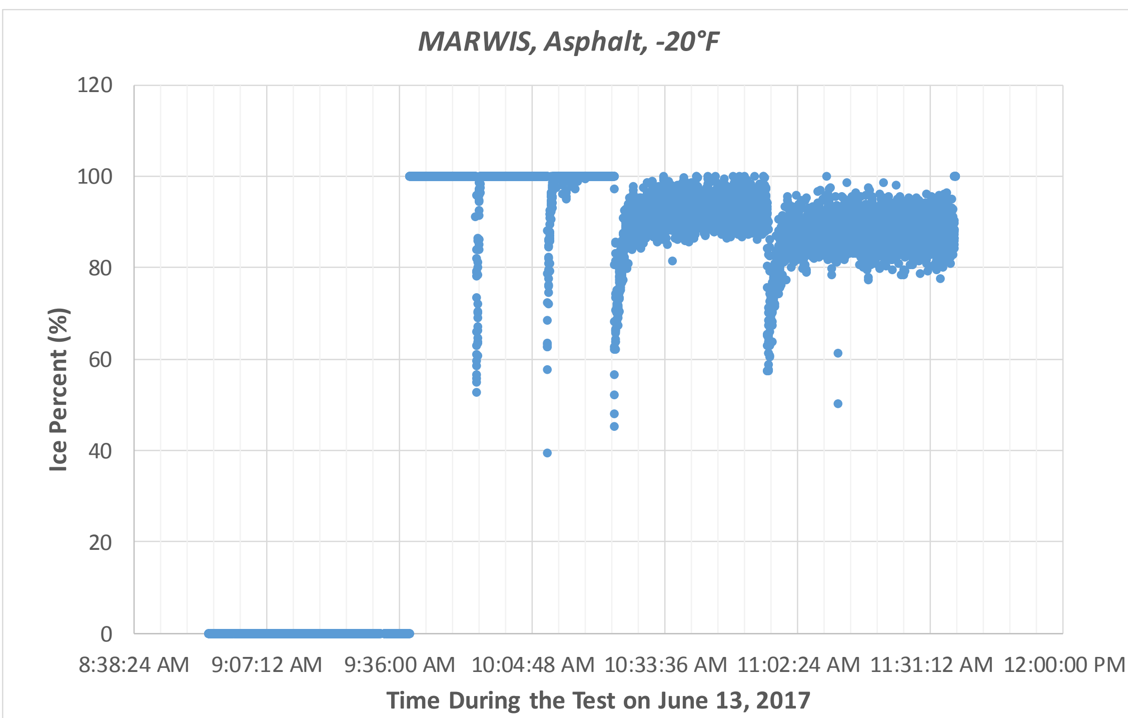


Figure 70. Ice Percent measured by the MARWIS sensor on asphalt pavement at -20°F test temperature

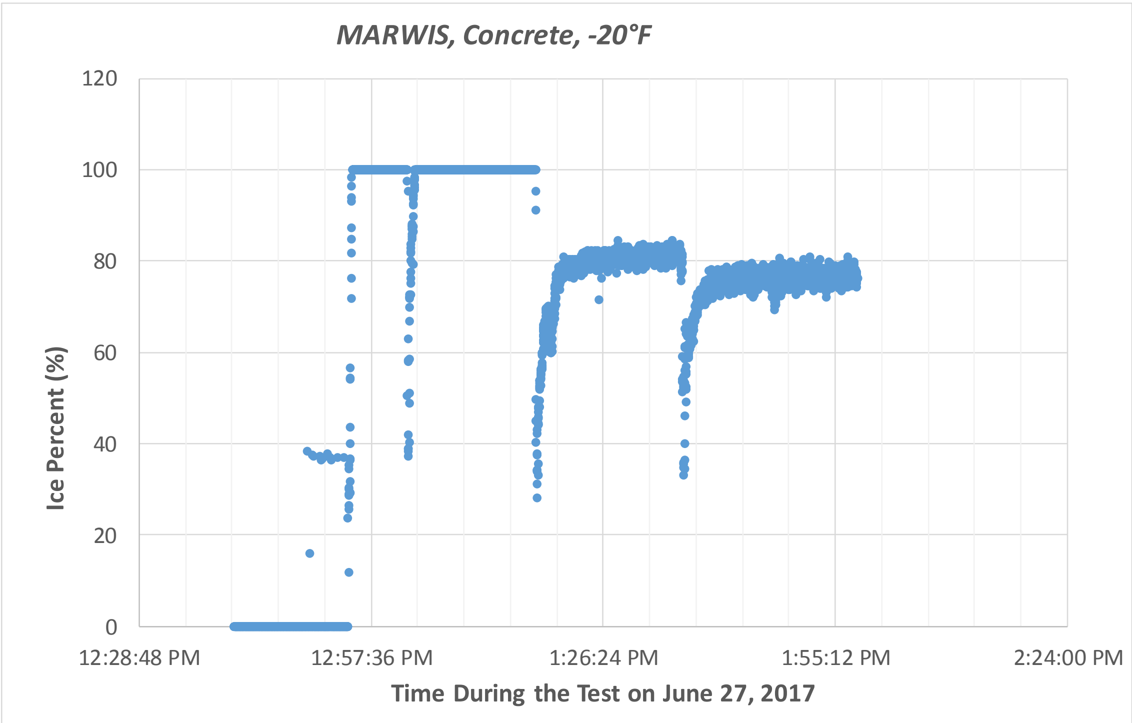


Figure 71. Ice Percent measured by the MARWIS sensor on asphalt concrete at -20°F test temperature (MC-20a)

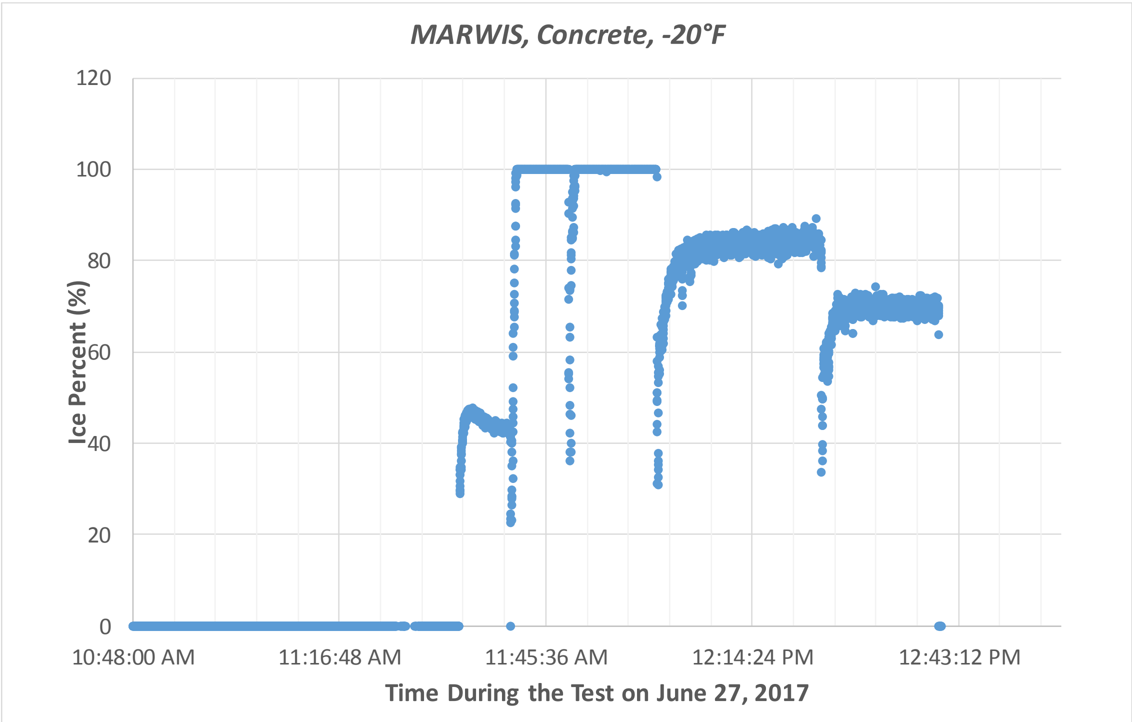
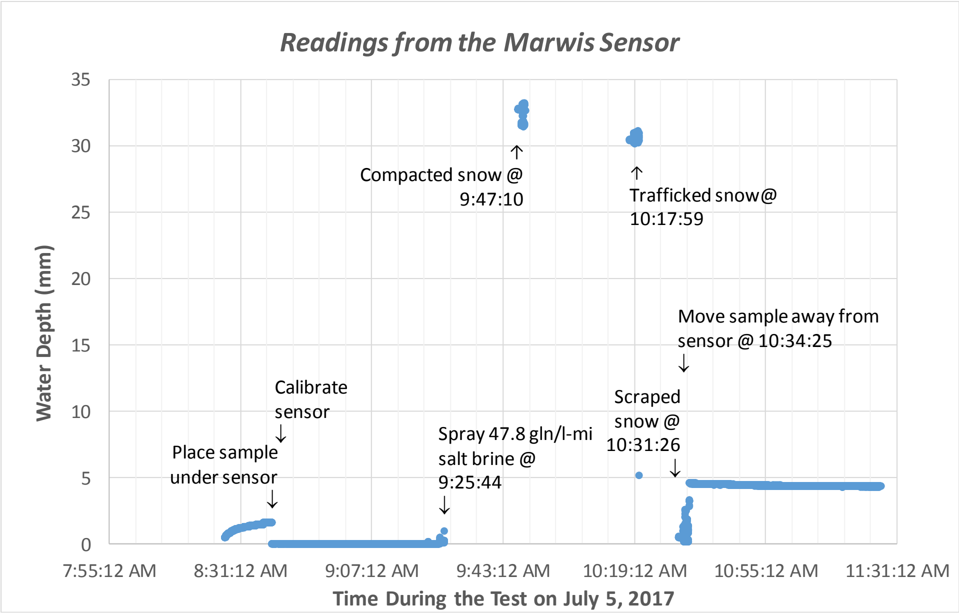


Figure 72. Ice Percent measured by the MARWIS sensor on concrete pavement at -20°F test temperature (MC-20b)

APPENDIX B. SNOW AND TRAFFICKING TESTING, ADDITIONAL FIGURES

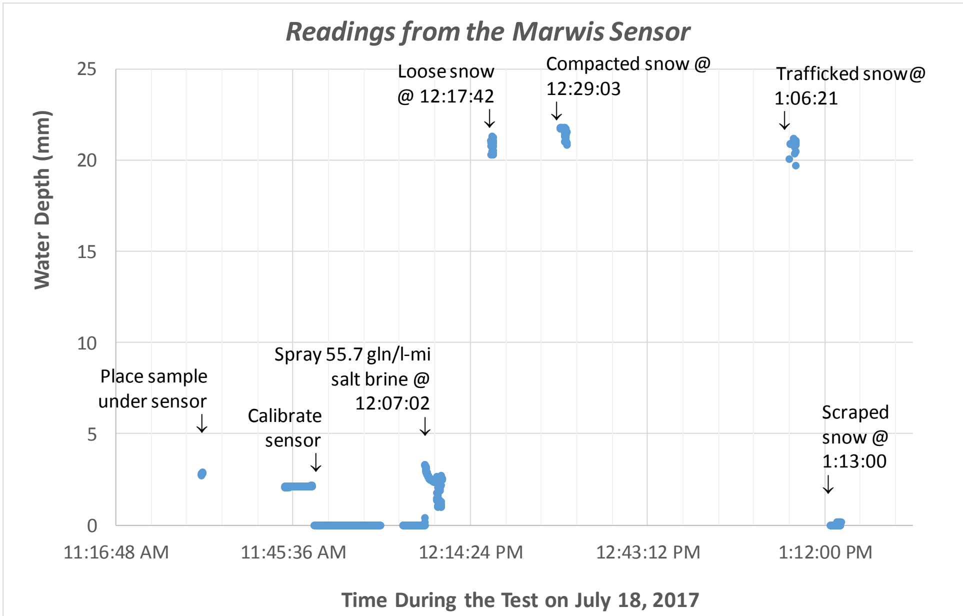
Water/Ice Depth

MARWIS



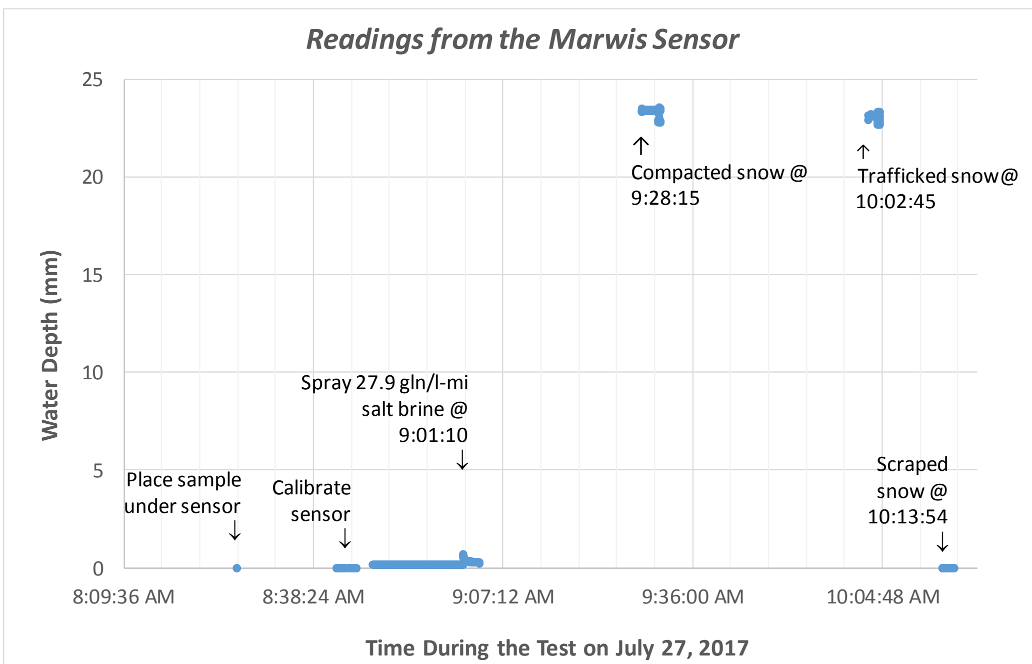
Data were collected from an asphalt sample at air and pavement temperature of 28°F.

Figure 73. Water depth data reported by the MARWIS throughout the snow trafficking testing



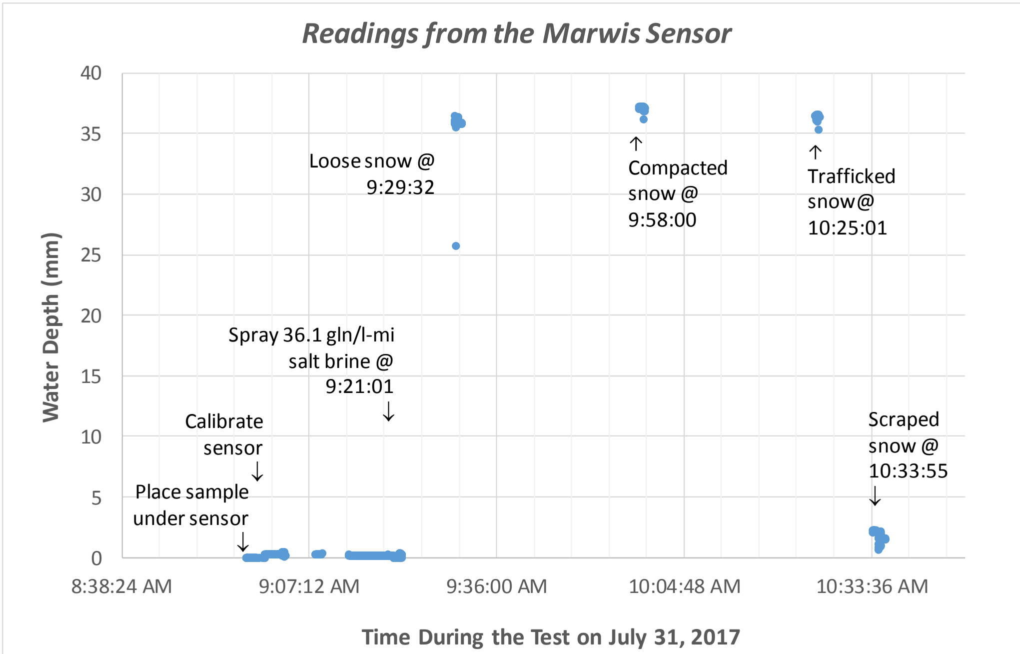
Data were collected from a concrete sample at air and pavement temperature of 28°F.

Figure 74. Water depth data reported by the MARWIS throughout the snow trafficking testing



Data were collected from a concrete sample at air and pavement temperature of 28°F.

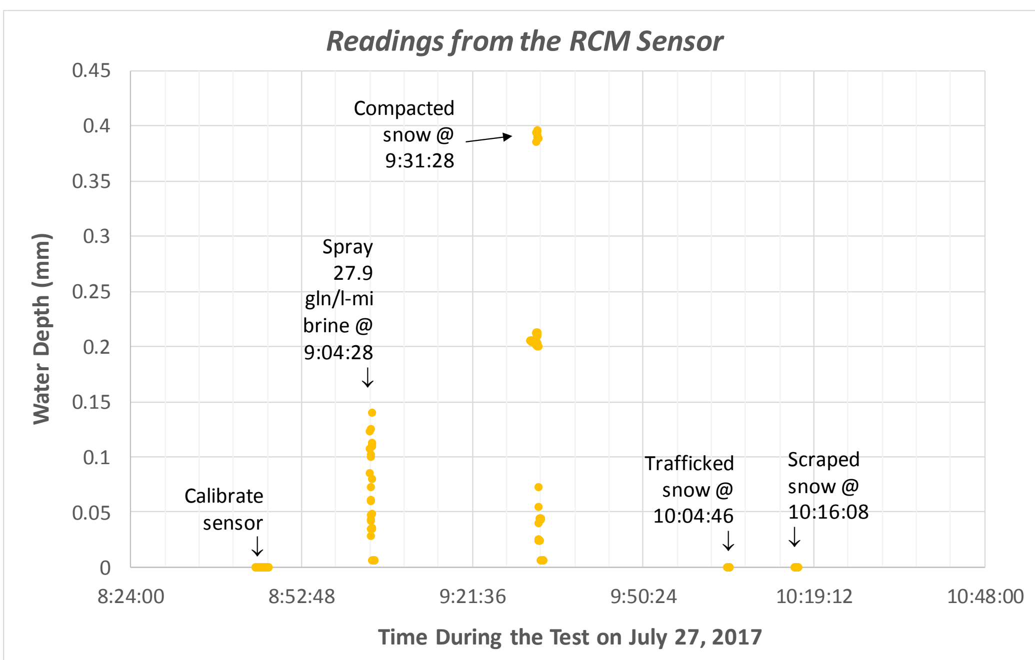
Figure 75. Water depth data reported by the MARWIS throughout the snow trafficking testing



Data were collected from an asphalt sample at air and pavement temperature of 28°F.

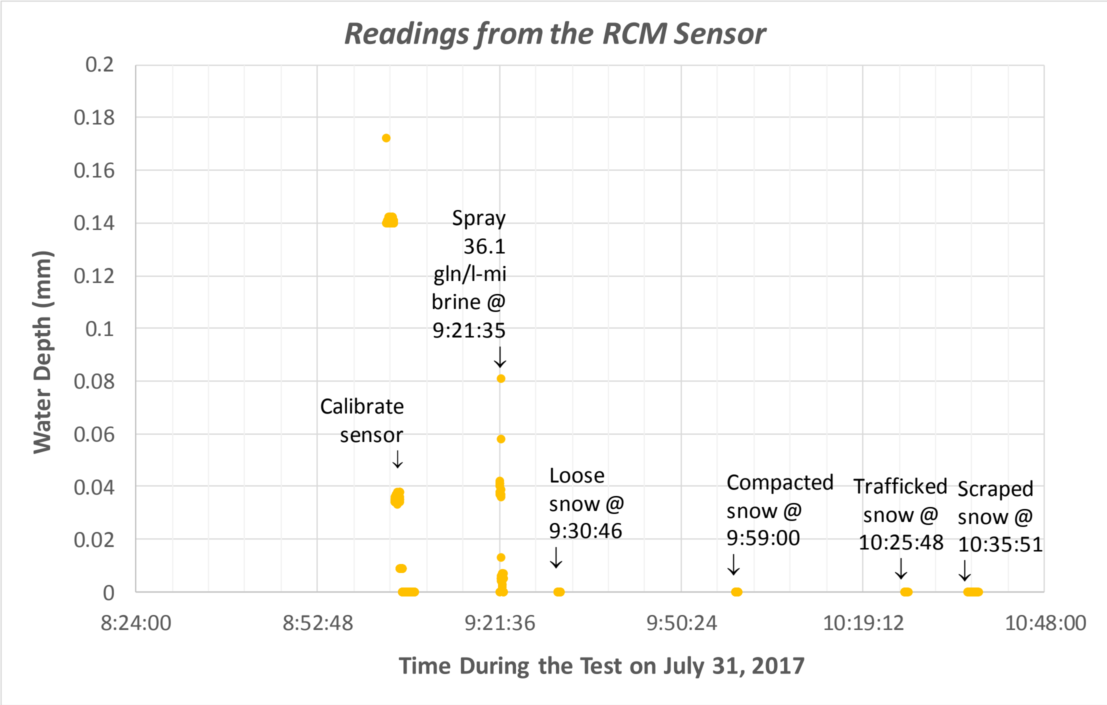
Figure 76. Water depth data reported by the MARWIS throughout the snow trafficking testing

Teconcer RCM411



Data were collected from a concrete sample at air and pavement temperature of 28°F.

Figure 77. Water depth data reported by the Teconer RCM411 throughout the snow trafficking testing

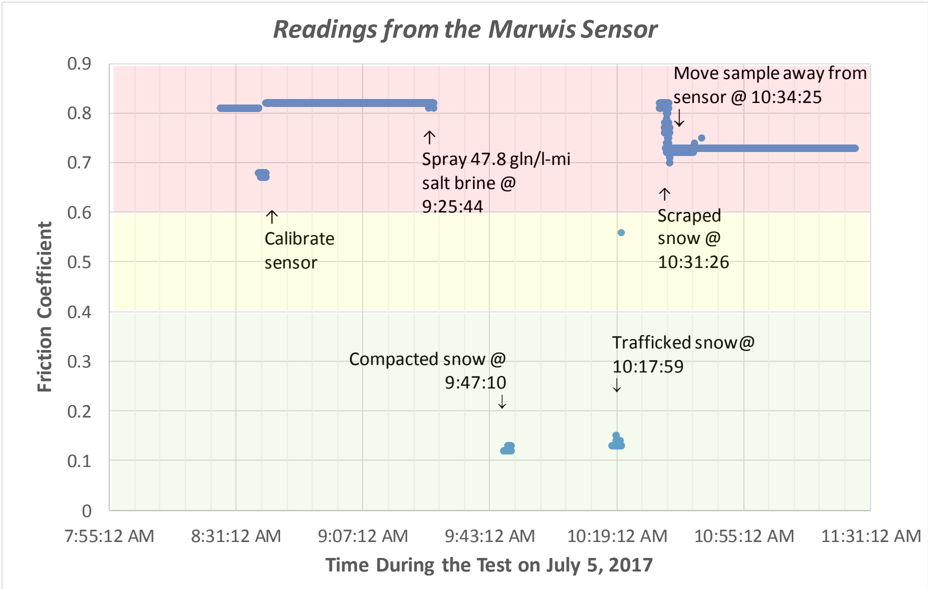


Data were collected from an asphalt sample at air and pavement temperature of 28°F.

Figure 78. Water depth data reported by the MARWIS throughout the snow trafficking testing

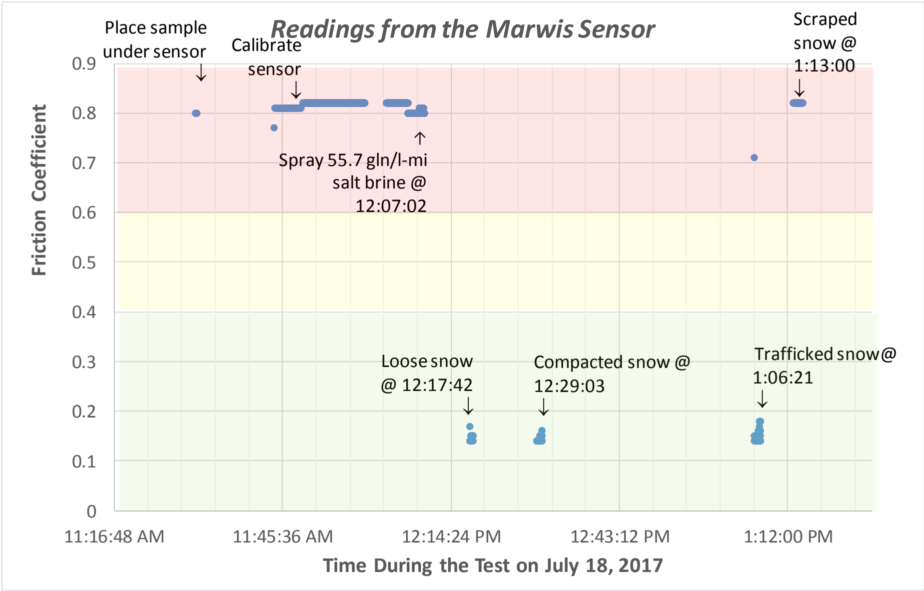
Friction

MARWIS



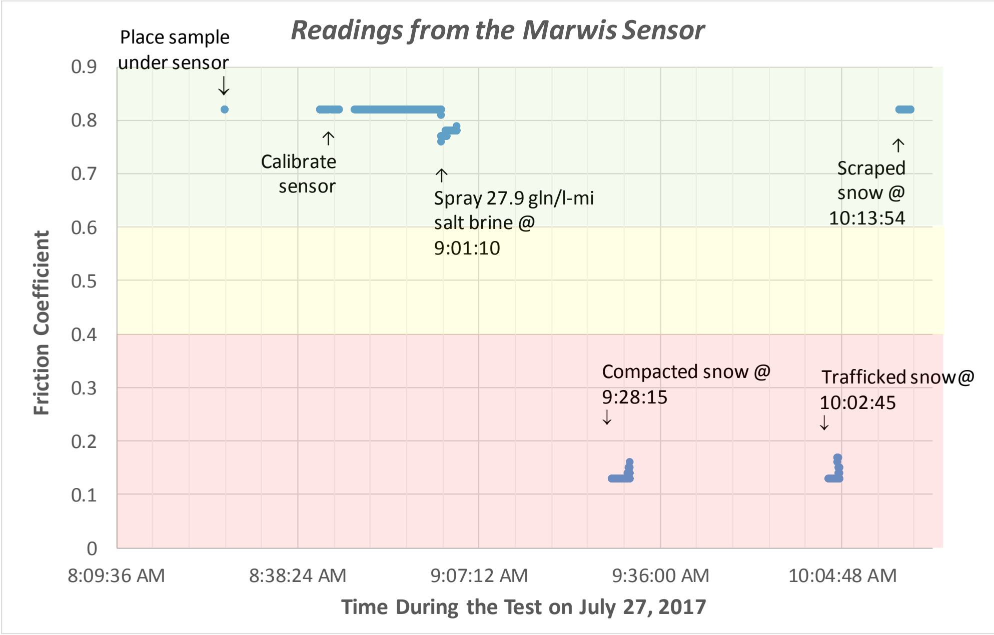
Data were collected from an asphalt sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and red is very low friction with loss of traction likely.

Figure 79. Friction coefficient data reported by MARWIS throughout the snow trafficking testing



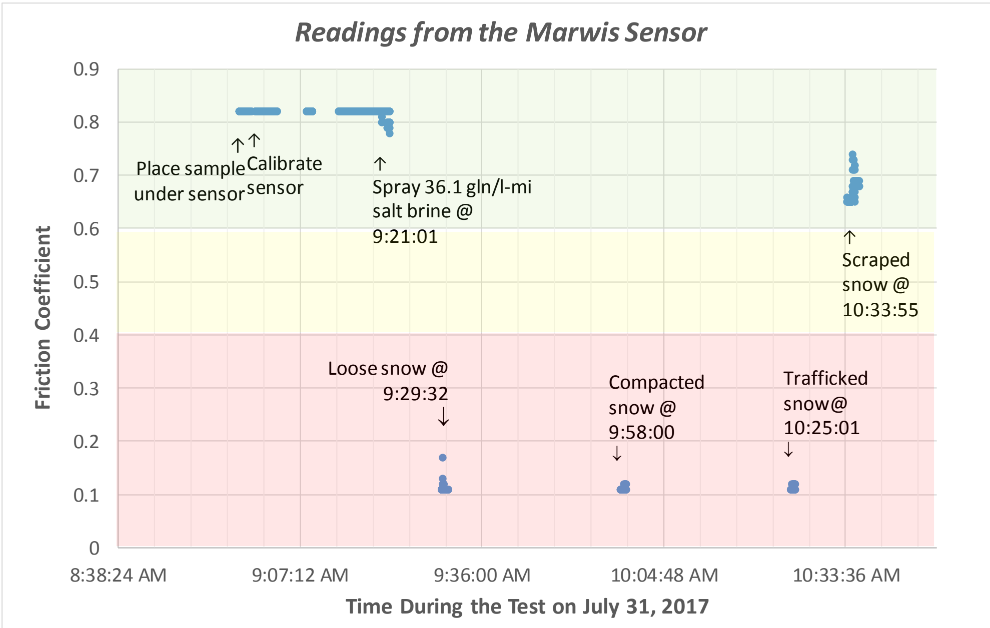
Data were collected from a concrete sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 80. Friction coefficient data reported by MARWIS throughout the snow trafficking testing



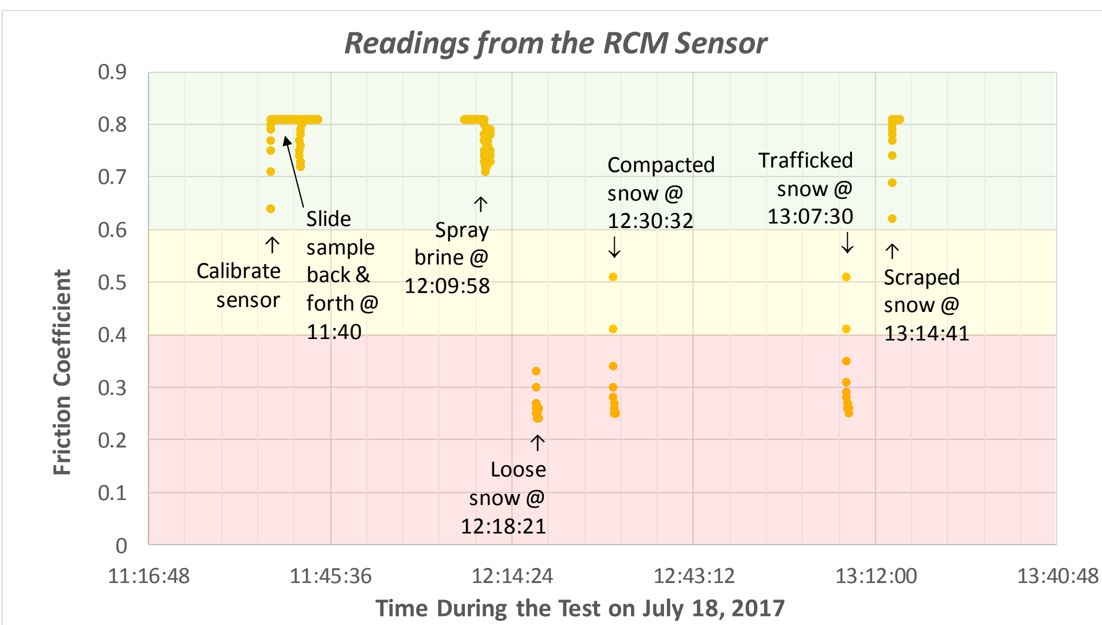
Data were collected from a concrete sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 81. Friction coefficient data reported by MARWIS throughout the snow trafficking testing



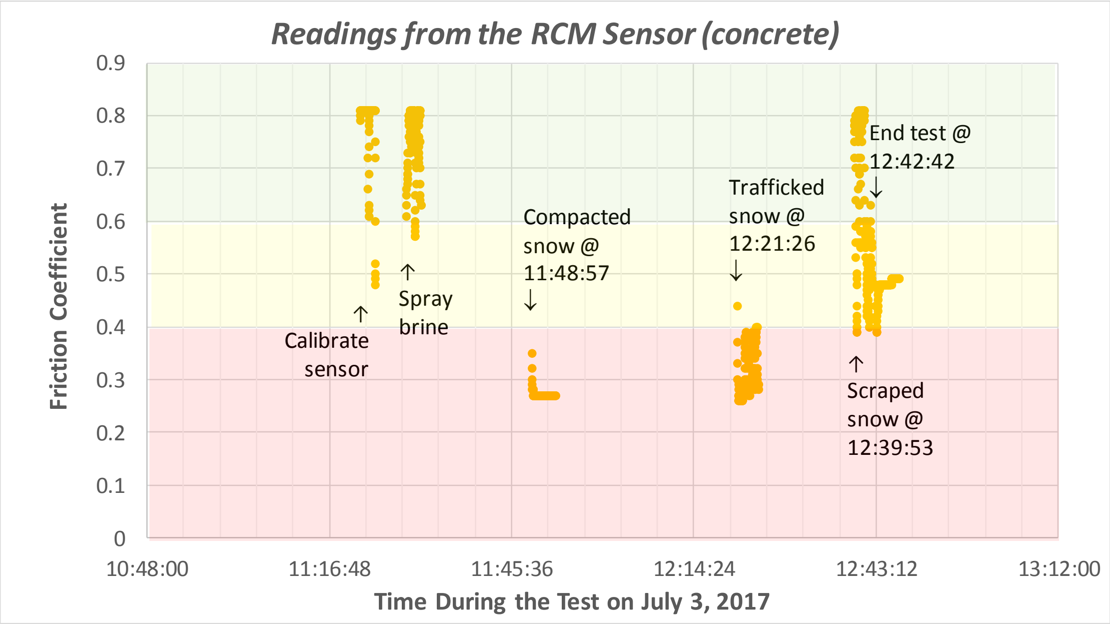
Data were collected from an asphalt sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 82. Friction coefficient data reported by MARWIS throughout the snow trafficking testing



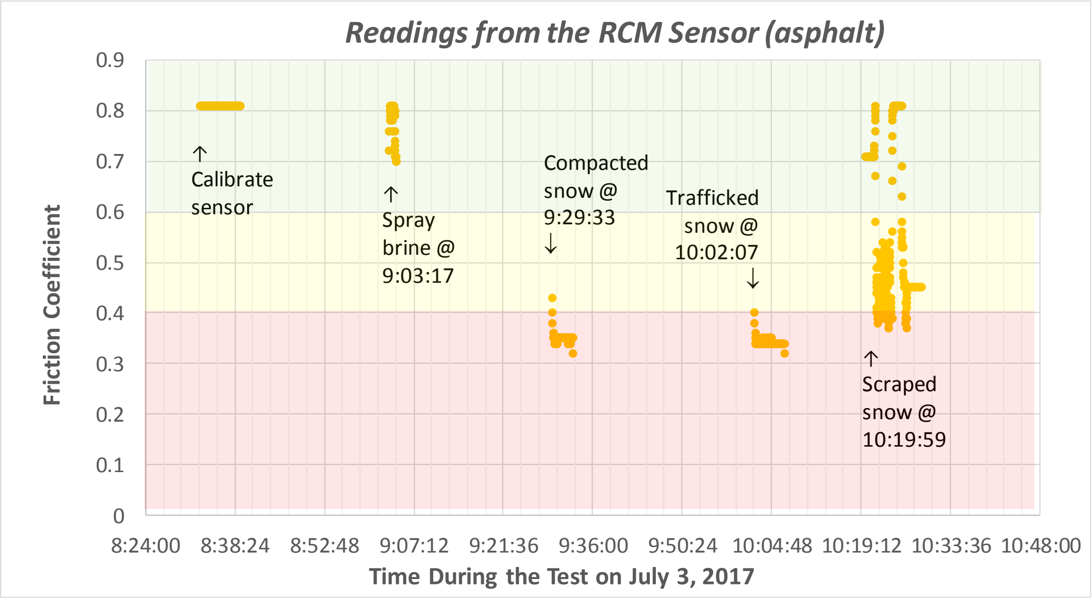
Data were collected from a concrete sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 83. Friction coefficient data reported by the Teconer RCM411 throughout the snow trafficking testing



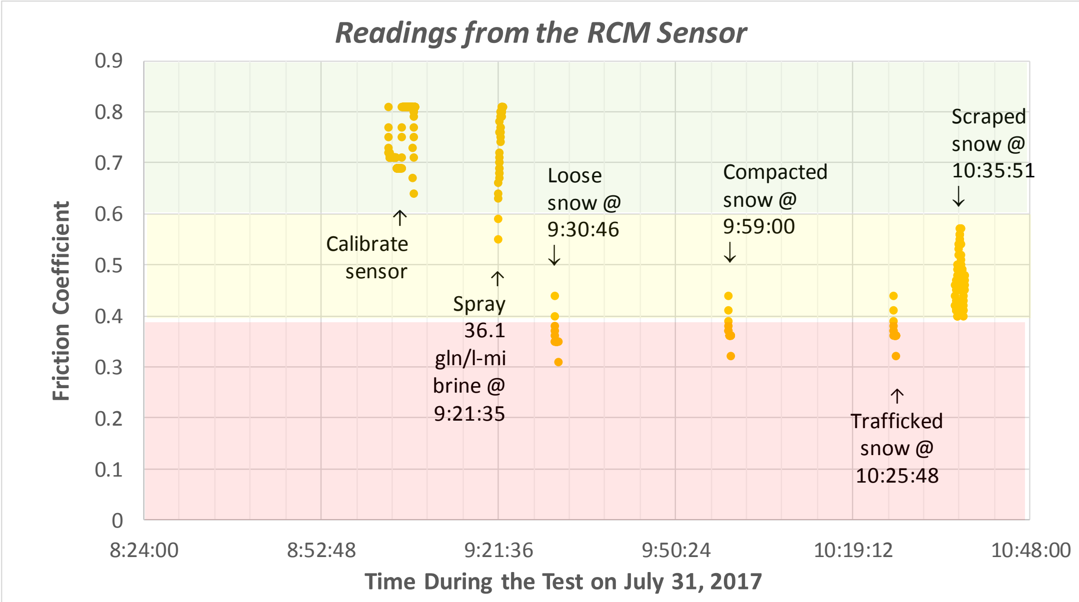
Data were collected from a concrete sample at air and pavement temperature of 28°F. The green shaded areas is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 84. Friction coefficient data reported by the Teconer RCM411 throughout the snow trafficking testing



Data were collected from an asphalt sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 85. Friction coefficient data reported by the Teconer RCM411 throughout the snow trafficking testing



Data were collected from an asphalt sample at air and pavement temperature of 28°F. The green shaded area is considered safe, the yellow is moderate friction and of concern, and the red is very low friction with loss of traction likely.

Figure 86. Friction coefficient data reported by the Teconer RCM411 throughout the snow trafficking testing

Pavement Surface Temperature

MARWIS

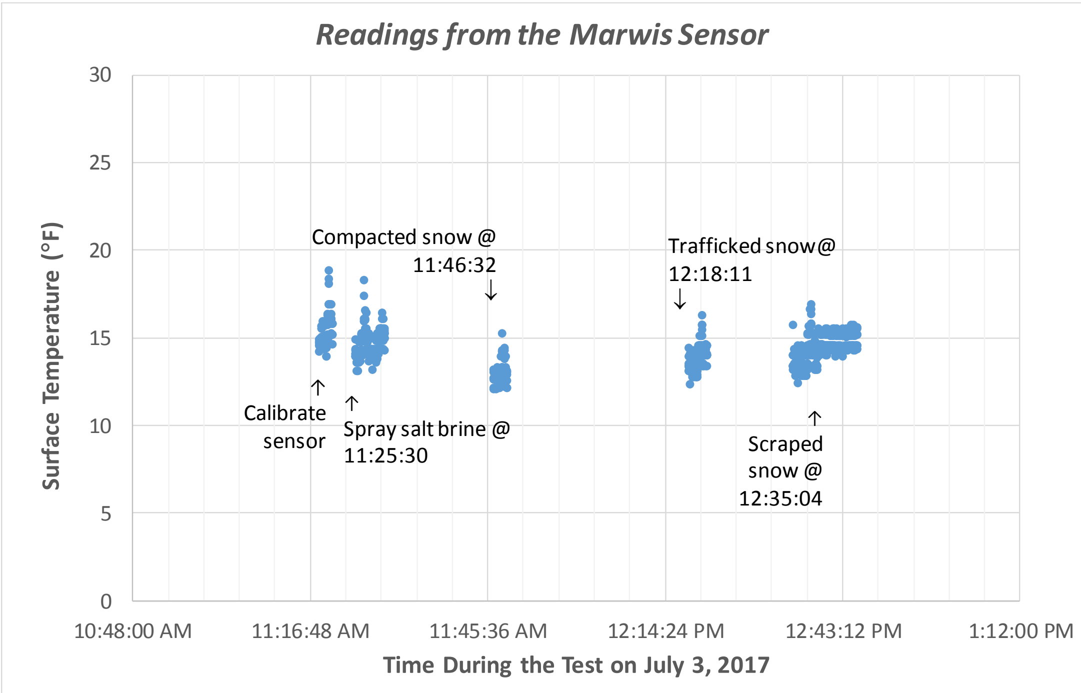


Figure 87. Pavement surface temperature data from the MARWIS sensor on concrete pavement at air temperature 28°F

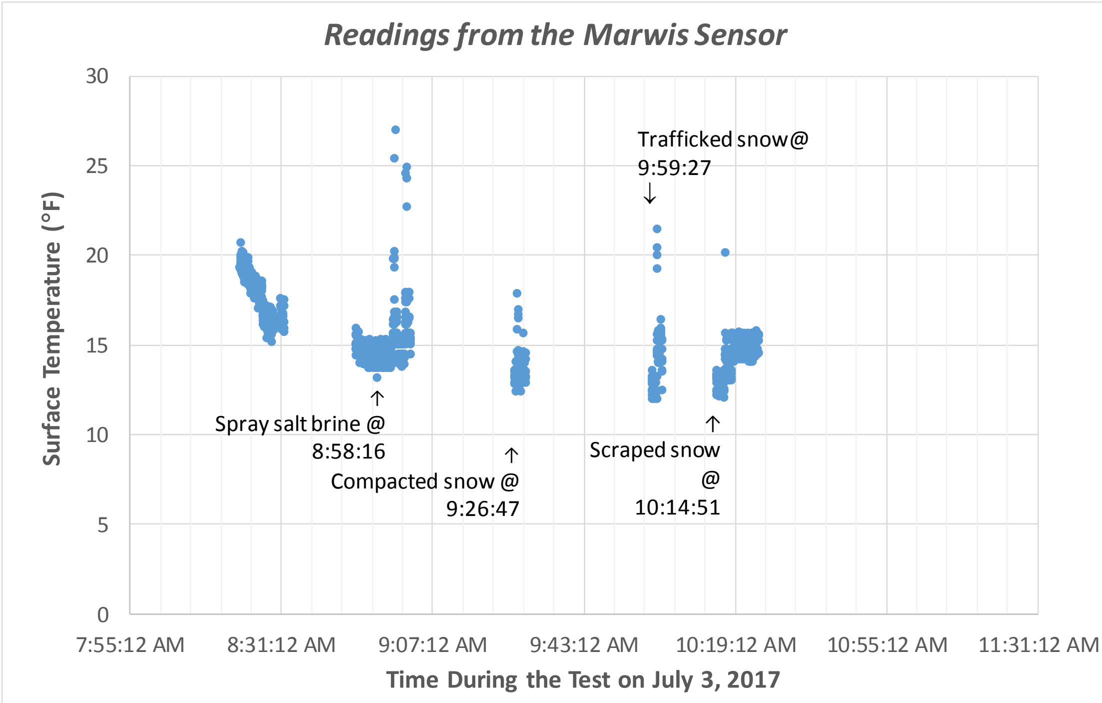


Figure 88. Pavement surface temperature data from the MARWIS sensor on asphalt pavement at air temperature 28°F

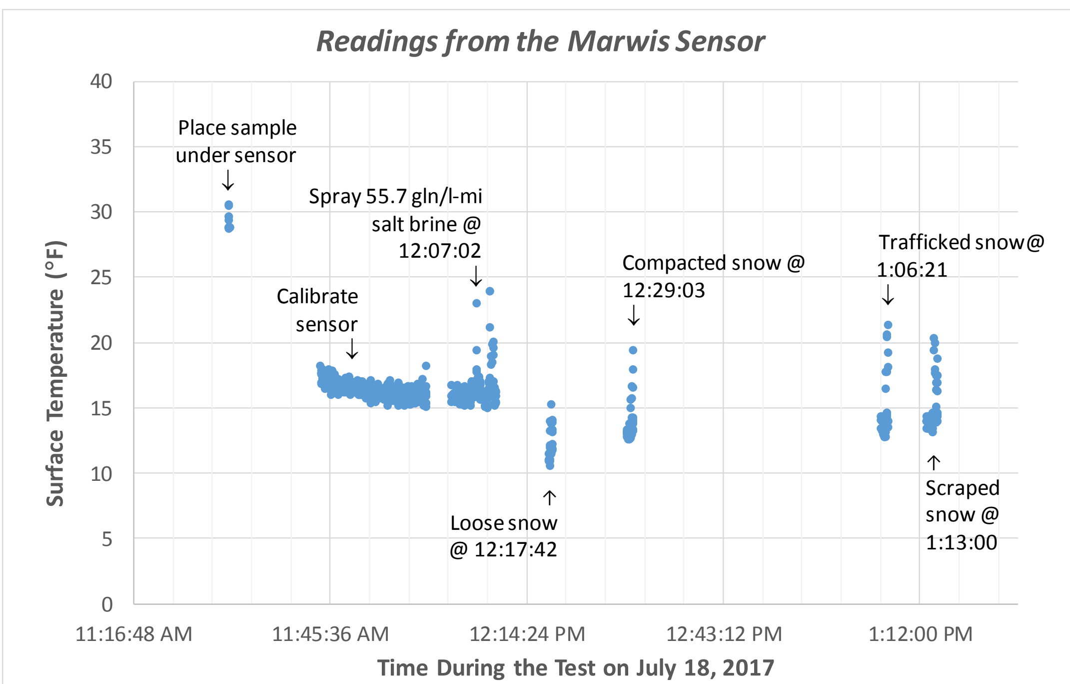


Figure 89. Pavement surface temperature data from the MARWIS sensor on concrete pavement at air temperature 28°F

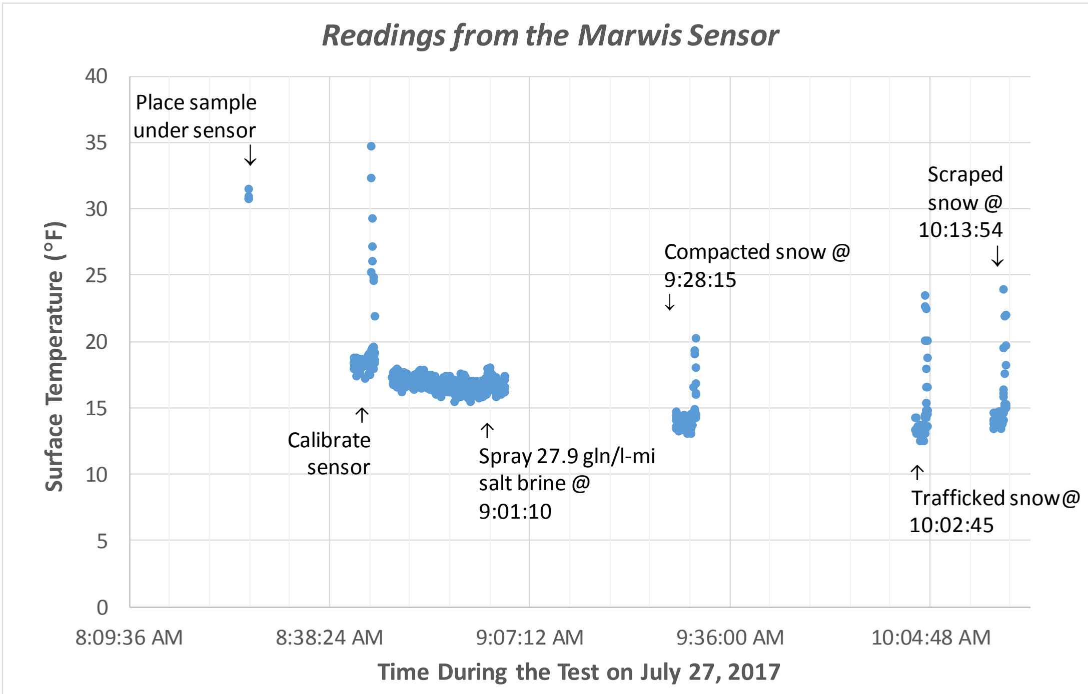


Figure 90. Pavement surface temperature data from the MARWIS sensor on concrete pavement at air temperature 28°F

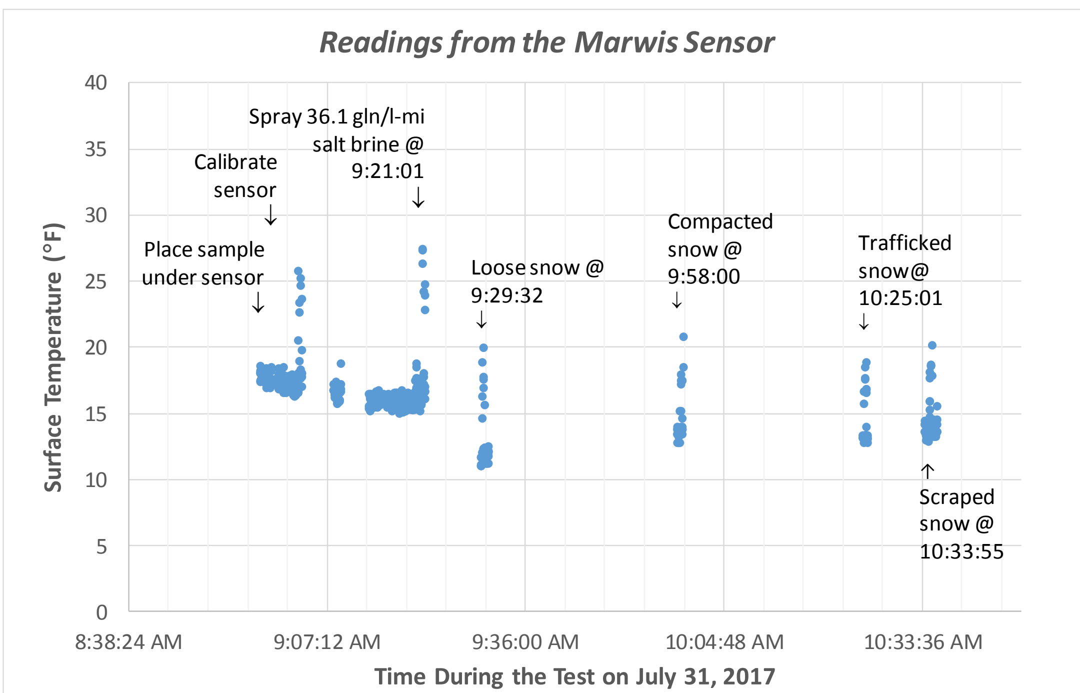


Figure 91. Pavement surface temperature data from the MARWIS sensor on asphalt pavement at air temperature 28°F

Teconer RCM411

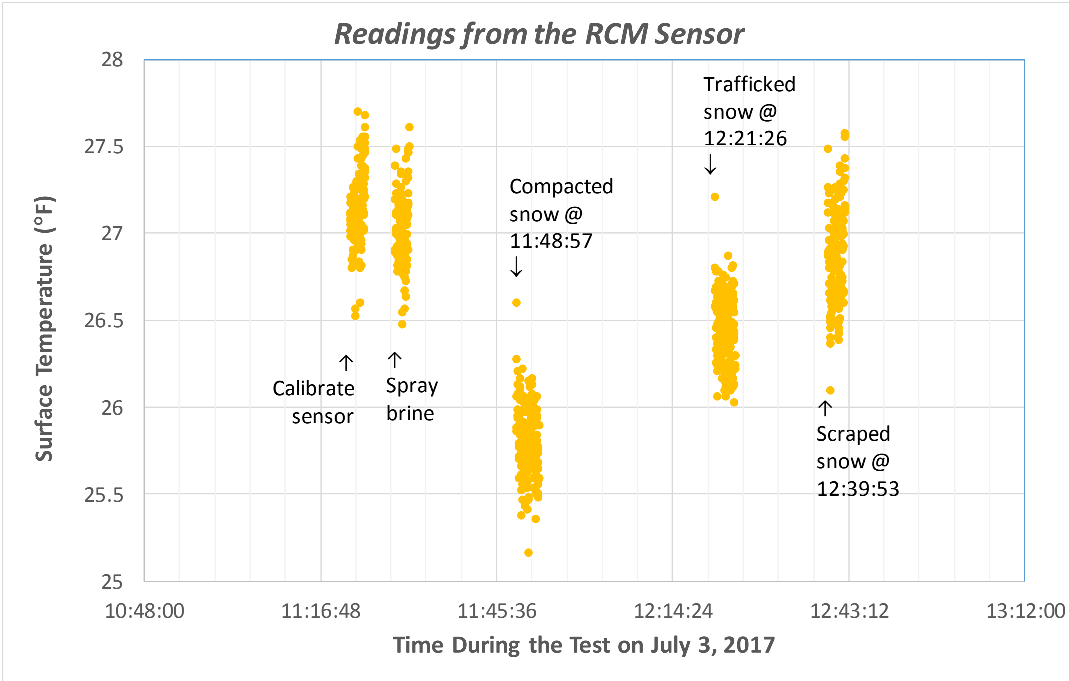


Figure 92. Pavement surface temperature data from the Teconer RCM411 sensor on concrete pavement at air temperature 28°F

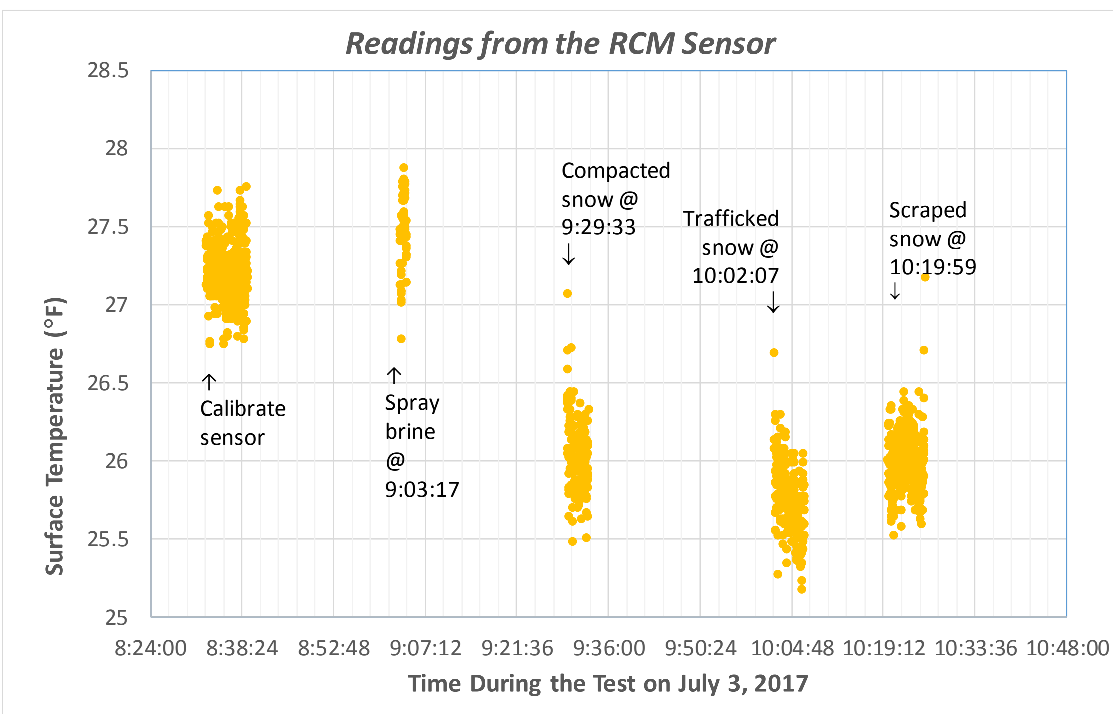


Figure 93. Pavement surface temperature data from the Teconer RCM411 sensor on asphalt pavement at air temperature 28°F

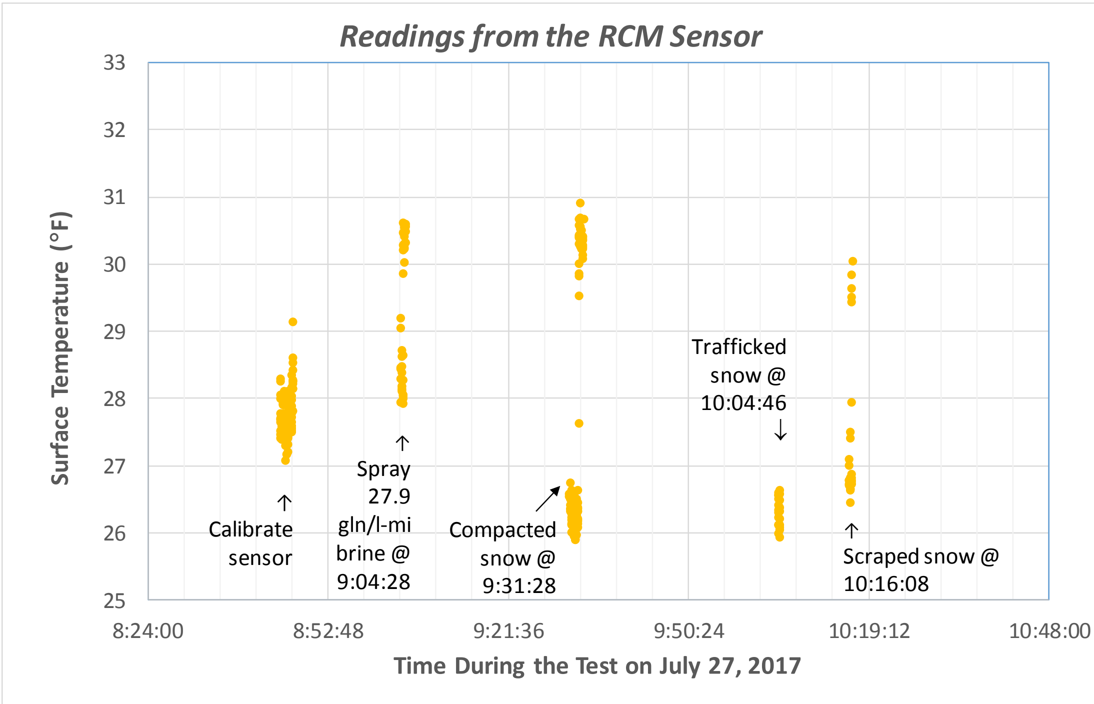


Figure 94. Pavement surface temperature data from the Teconer RCM411 sensor on concrete pavement at air temperature 28°F

MARWIS Ice Percent

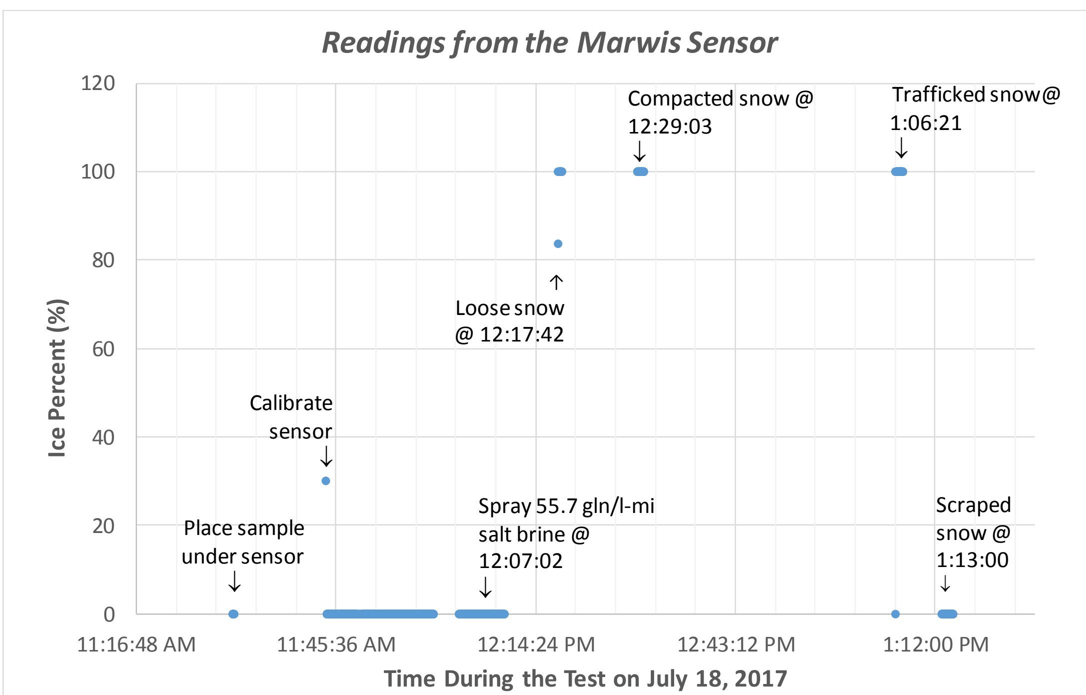


Figure 95. Percent ice detected on the pavement surface by the MARWIS sensor on concrete pavement

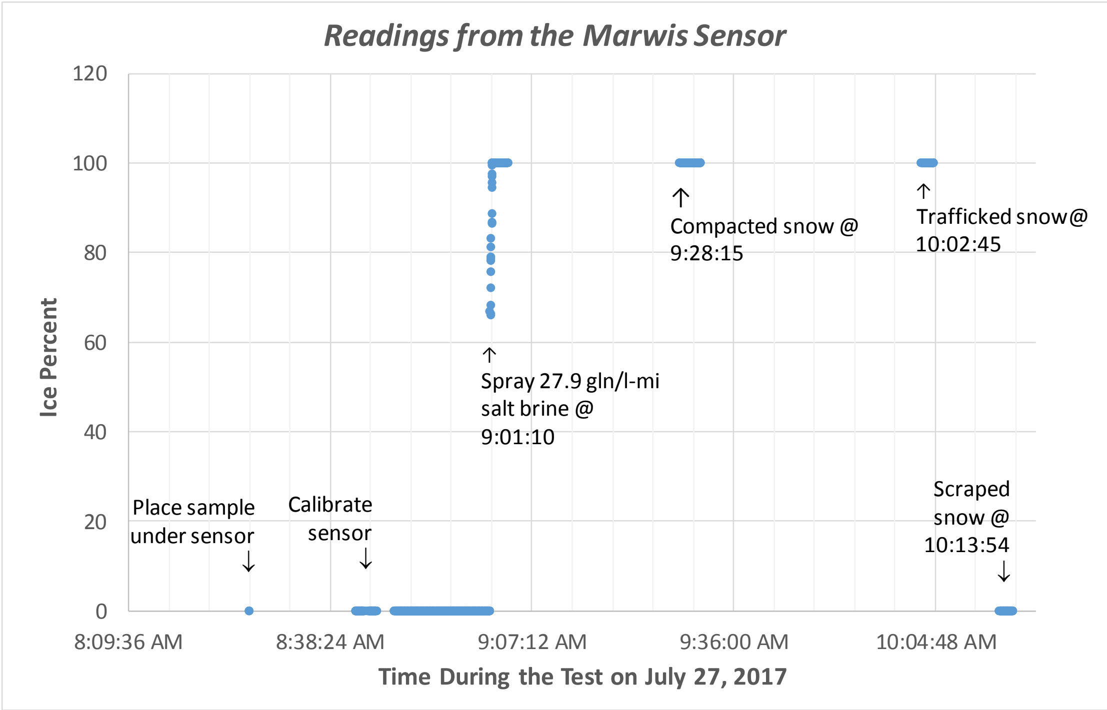


Figure 96. Percent ice detected on the pavement surface by the MARWIS sensor on concrete pavement

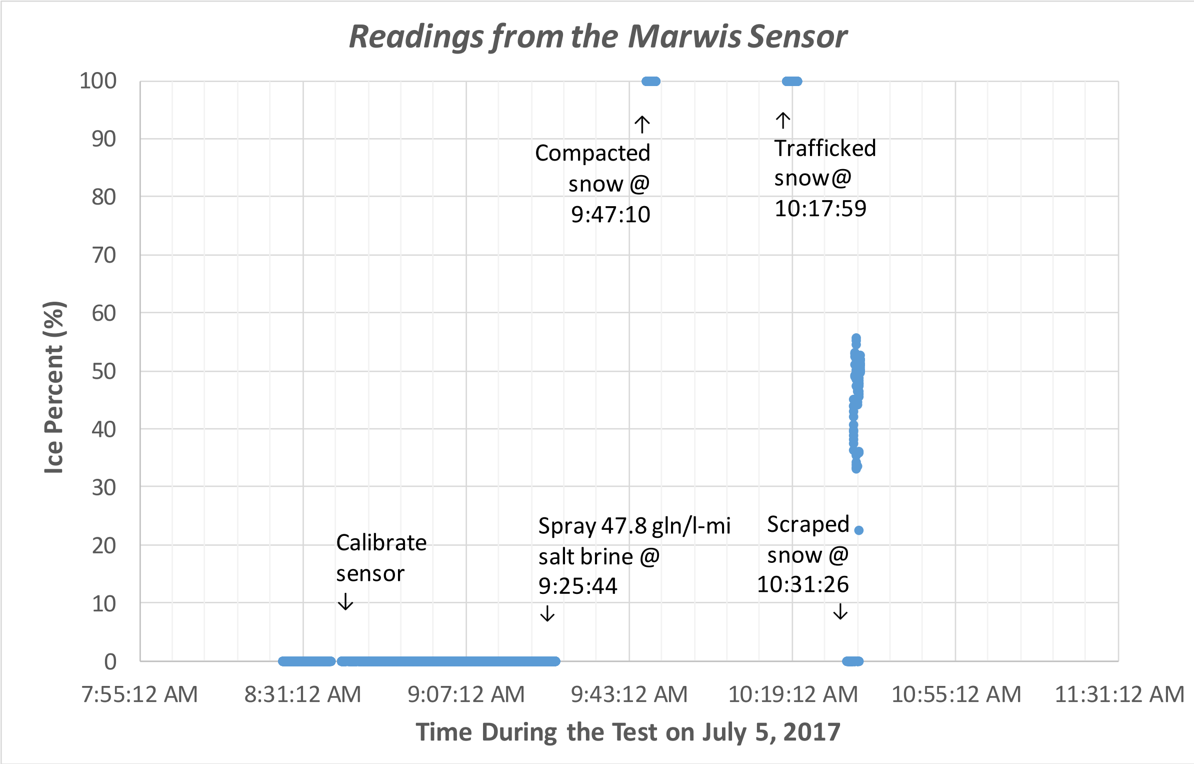


Figure 97. Percent ice detected on the pavement surface by the MARWIS sensor on asphalt pavement

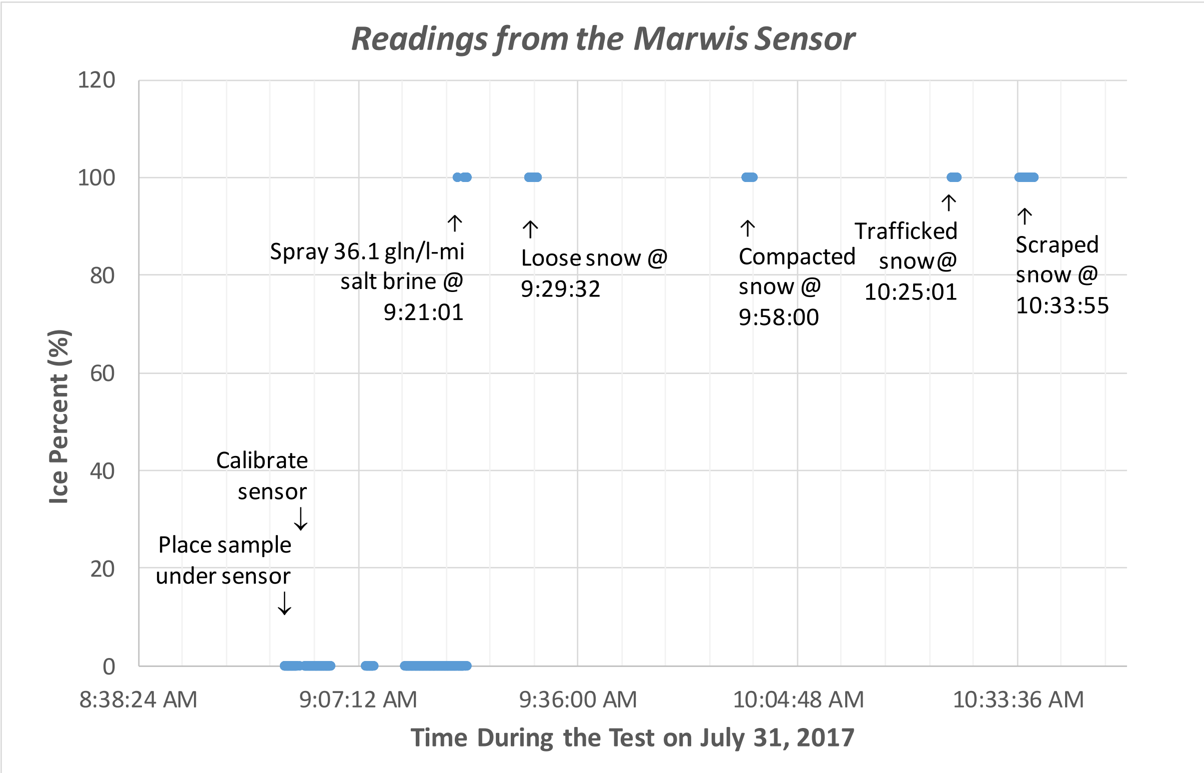


Figure 98. Percent ice detected on the pavement surface by the MARWIS sensor on asphalt pavement

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