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Quantifying Salt Concentration on Pavement: Phase I

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Aurora Project 2013-04

Final Report
May 2015

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

Winter maintenance operations typically involve the application of salts to roadways to combat the formation of ice or snow pack on the road surface. Precise knowledge of pavement conditions, especially the amount of salt remaining on the pavement surface, is needed to maximize the benefits and reduce the negative effects of road salt usage. Salinity sensing technologies are effective solutions to meet such needs.

The focus of this phase of the research was to report on available mobile salinity measurement technologies. Technologies were identified through a literature search, a review of patents, information provided by vendors and manufacturers, survey responses, and follow-up interviews.

A survey was conducted to gather information from winter maintenance professionals at state, provincial, and local transportation agencies on their experience with salinity sensors in snow and ice control operations. Responses were received from 6 countries and 17 US states. Respondents expressed significant interest in the use of mobile salinity sensors, with 90% indicating that they either would consider using this technology or were unsure and only 10% indicating that they would not consider using this technology. Respondents indicated that cost, accuracy, and dependability were of greatest concern and were potential barriers to implementation.

Three types of salinity sensors were identified: in-pavement sensors, portable sensors, and vehicle-mounted sensors. Seven mobile salinity sensors were identified as potential candidates for Phase II field trials.

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QUANTIFYING SALT CONCENTRATION ON PAVEMENT: PHASE I

Final Report
May 2015

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INTRODUCTION/BACKGROUND

Maintenance agencies in northern climates are continually challenged to provide a high level of service (LOS) and improve safety and mobility on winter pavement in a cost-effective and environmentally responsible manner. Chloride-based salts play a key role as freezing point depressants in anti-icing, de-icing, and pre-wetting operations, yet there are increasing concerns about their cost and negative impacts on motor vehicles, maintenance equipment, transportation infrastructure, and the natural environment. The ultimate goal of many best practices used in winter maintenance operations is to apply the right type and amount of materials in the right place at the right time. To ensure the appropriate application rate of salt or salt brine on pavement, there is a need to identify, evaluate, and potentially improve technologies that provide better and quantitative information about pre-existing/residual salt concentration on the pavement prior to new application of salt or salt brine. This need has been identified as a high priority by the National Winter Maintenance Peer Exchanges (in 2007 and 2009) as well as by the Aurora Consortium.

Salinity sensors have been traditionally employed in road weather information systems (RWIS), which focus on the pavement conditions and meteorological conditions of a small sample area (typically less than 0.1 ft^2) (Fleege et al. 2006, Strong and Fay 2007). The working mechanism of such in-pavement salinity sensors generally involves the measurement of brine conductance, a passive approach, or freezing point depression, an active approach (Turune 1997). There are also portable instruments, such as the Boschung SOBO-20, which sprays a water and acetone mixture onto the enclosed pavement surface area and subsequently calculates the salt quantity based on the electrical conductivity of the fluid (Lysbakken and Lalague 2013). More recently, non-invasive sensors that rely on algorithms to estimate salt concentrations on pavements have been used (Bridge 2008).

Salinity sensors can be used to monitor residual salt concentrations on the road surface, helping maintenance managers make educated decisions related to chemical reapplication and avoid over-application (Highways Agency 2007, Ye et al. 2011, Ruiz-Llata et al. 2014a, b). Salinity sensors installed on maintenance vehicles could provide instant salt concentration information along entire stretches of roadways. The use of salinity sensors in the application of road salt can address a spectrum of considerations by identifying where salt is being over-applied to areas, such as congested urban roadways, where there is risk of salt concentrations on the pavement dropping below a critical threshold and causing a safety issue. Benefits gained from the use of salinity sensors may include the following:

- The ability to assess whether treatments are holding out or retreating is necessary and, if the latter, the amount of additional salt or brine
- Improved pavement condition forecasts
- The limiting of applications to only what is necessary in salt-vulnerable or environmentally sensitive areas or to avoid structural damage
- Improved chemical application decisions, i.e., whether more is needed or the salt on the pavement surface is sufficient
- The dynamic control of spread rates based on measurements

- Reduced use of products, leading to product savings, and the provision of direct and indirect savings for stakeholders and taxpayers
- Improved safety for road users
- Improved timing and increased precision of applications
- The tracking of salt use

If placed on a mobile platform, such as a snowplow, these sensors can monitor salt concentrations along entire stretches of roadway. This information can then be used to obtain more accurate chemical application rates. In other words, on-vehicle salinity sensors could be a crucial component of mobile RWIS. A more advanced scenario would entail the integration of salinity sensor readings with automatic spreader controls to apply the right amount of chemicals in the right place. Note that integration has been an underlying goal in several US winter maintenance vehicle-based technology projects, including RoadView, the Minnesota Department of Transportation's (MnDOT) Advanced Snow Plow, and the Highway Maintenance Concept Vehicle. There is continued support in the winter maintenance community for similar vehicles that use integrated technologies to improve operations and safety, including automatic vehicle location (AVL), surface temperature sensors, freezing point and ice presence detection sensors, salinity sensors, snowplow blade position sensors, and application rate sensors.

Summary of Survey Results

A survey was used to gather information from winter maintenance professionals at state, provincial, and local transportation agencies on their experience with salinity sensors used in snow and ice control operations to measure salt concentration on pavements. A summary of the survey results is provided here, and detailed responses to the survey questionnaire can be found in Appendix A. The survey consisted of 14 questions. A total of 50 people accessed the survey, with 33 providing responses. Responses were received from 6 countries and 17 US states. More than half of the survey respondents were from state or provincial winter maintenance agencies, with about a third of the responses from companies and less than 10% of responses from universities.

Just under half (44%) of respondents indicated that they use salinity sensors in winter maintenance operations. Responding agencies that do use salinity sensors included state (California Department of Transportation [Caltrans], Kansas Department of Transportation [KDOT], Massachusetts Department of Transportation [MassDOT], MnDOT, North Dakota Department of Transportation [NDDOT], New York State Department of Transportation [NYSDOT], Ohio Department of Transportation [ODOT], Utah Department of Transportation [UDOT], Wisconsin Department of Transportation [WisDOT], and West Virginia Department of Transportation [WVDOT]), provincial (Ontario Ministry of Transportation, Brun-Way Highway Operations), or government-run transportation agencies (Norwegian Public Roads Administration, AIBAN Vinterservice [Denmark]), along with responses from two product manufacturers and one university. In-pavement salinity sensors were used more commonly, with two respondents indicating that they use portable but not vehicle-mounted sensors (Boschung SOBO), and one respondent (a manufacturer) stating that they use a vehicle-mounted salinity sensor (Teconer RCM411). The following responding transportation agencies indicated that they do not use salinity sensors: Colorado Department of Transportation (CDOT), Iowa Department of Transportation (Iowa DOT), MnDOT, Nevada Department of Transportation (NDOT), NDDOT, Pennsylvania Department of Transportation (PennDOT), and Alberta Ministry of Transportation. Respondents that indicated that they do not use salinity sensors provided the following reasons:

- They have salinity sensors but do not trust the measurements and have reliability issues with the sensors.
- Maintenance of the sensors is a challenge given limited budgets.
- They have concerns that the sensors are not rugged enough to withstand the harsh environment of winter maintenance operations.
- Lack of knowledge about the sensors.

For in-pavement salinity sensors used by respondents, reported purchase costs ranged from $1,300 to $5,500, with the cost varying by the type of sensor used. Annual maintenance costs ranged from $0.00 to $300, with one agency reporting about $1,100 for the annual maintenance of each RWIS site, including maintenance of the salinity sensors. The service life reported for in-pavement sensors was 3 to 10 years, with one respondent commenting that unless the puck is cut out, it needs to be replaced during paving operations. In-pavement salinity sensors were reported as being mounted just inside the wheel path, 1 ft outside the wheel path, in the wheel path or driving lane, on bridge decks, or as specified by the manufacturer.

For portable but not vehicle-mounted salinity sensors (Boschung SOBO), reported purchase costs ranged from $6,300 to $7,300. Annual maintenance costs of $146 were reported. A 20-year service life was reported for the Boschung SOBO-20 by one agency, while the responding university reported a lot of problems with the SOBO device. An advantage of the portable device provided by one respondent was that multiple readings could be taken across the road.

For vehicle-mounted sensors, the Teconer RCM411 was the only reported sensor. This sensor measures friction and other parameters. The friction value can then be converted to brine fraction or salt concentration. (Note: The capability of this sensor to report this data is not yet available. See the section on the Teconer RCM411 for more information.) A purchase cost of $9,000 was reported, with annual maintenance costs of about $100, and a service life of 5 to 10 years was estimated. The sensor was reported to be mounted at the front or rear of the vehicle. This information was provided by the manufacturer.

The respondents that use salinity sensors report that they are used to determine the following:

- Freeze point
- Presence of ice
- Risk of refreeze
- Chemically wet road surface
- Road condition forecasts
- Whether or not to apply grit or anti-ice; adjustments to the application rate

- Residual salt concentration on the road surface

Respondents were asked when and how salinity sensor data are used, and the following responses were provided:

- The limited data collected is rarely used or occasionally used.
- Staff use these data in the winter, and the data are input into a maintenance decision support system (MDSS).
- This information is used by the weather and pavement forecast vendor or for road condition forecasting.
- This information is used during and after each storm to check for proper application rate.
- This information is used during winter storm events.
- This information is collected every day after salting until salting is done for the year.

In general, the accuracy of the salinity sensors was reported to be less than 75% for in-pavement salinity sensors, while a few respondents indicated that they were unsure and had never tested the accuracy. The portable (not vehicle-mounted) sensor (Boschung SOBO) was reported to be more than 90% accurate by one respondent and of questionable accuracy by another. The measurement results for the vehicle-mounted sensor (Teconer RCM411), which measures friction, were reported by the manufacturer to have an error of 3% when converted to brine fraction.

Based on the survey responses, there appears to be a lot of interest in the use of mobile salinity sensors. When respondents were asked if they would consider using this technology, 90% indicated that they would, they would consider it, or that they are not sure, while only 10% indicated that they would not consider using this technology (Kansas DOT and PennDOT). Respondents indicated that cost, accuracy, and dependability were of greatest concern with this technology, as well as potential barriers to implementation.

MOBILE SALINITY SENSING TECHNOLOGY

This chapter presents information on mobile/vehicle-mounted salinity sensing technology. The information presented in this chapter was found through a literature search, a review of patents, information provided by vendors and manufacturers, survey responses, and follow-up interviews. The information presented is organized by the physical measurement characteristics of each sensor. Information on in-pavement and portable but not vehicle-mounted salinity sensing technology can be found in Appendix B.

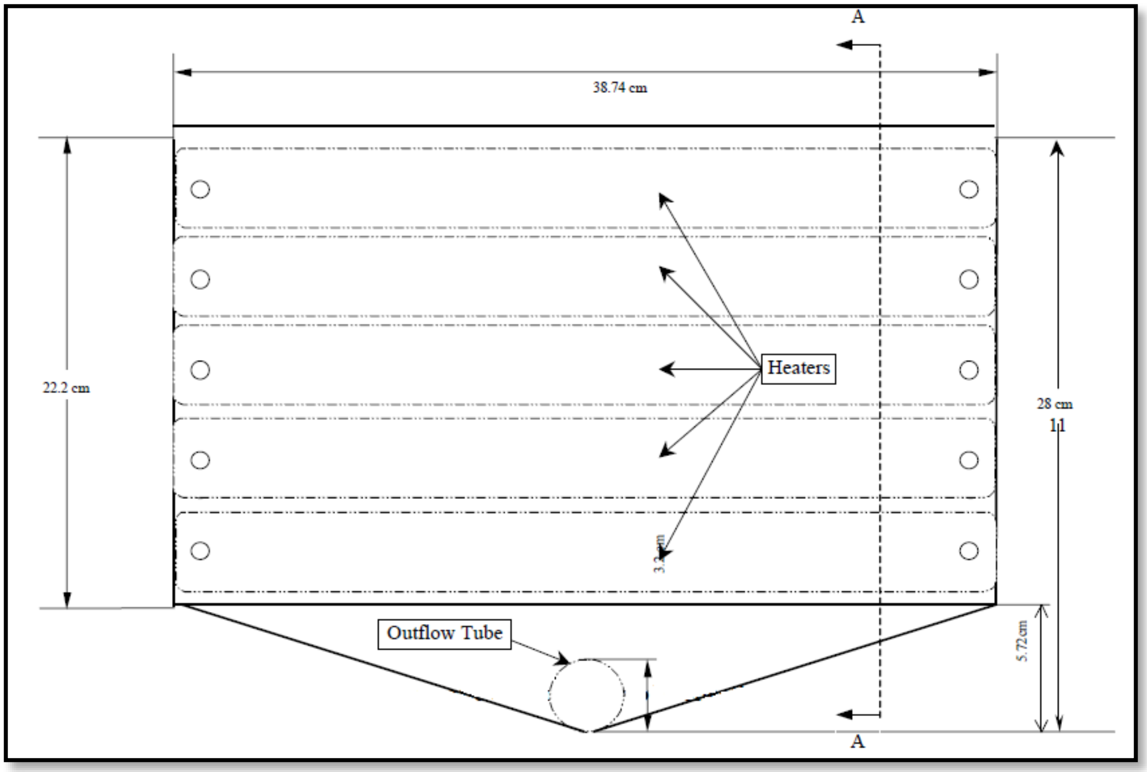
Electrical Conductance

In 2000, a portable salinity detection device was developed by the University of Connecticut (Figure 1).

Garrick et al. 2002, New England Transportation Consortium

Figure 1. Portable salinity sensor deicer collection box (left) and on-vehicle mounting (right)

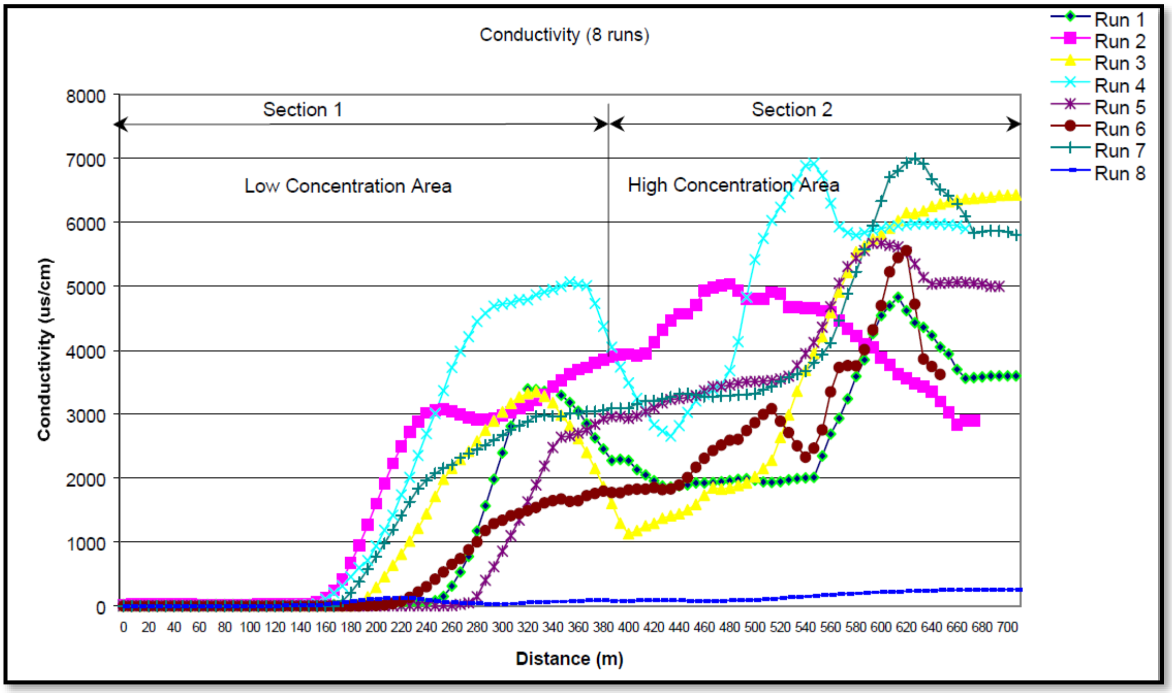
This device directly measures the residual salt concentration in tire splash from the road surface by testing the splash's electrical conductivity. A heater is used to melt the tire splash to determine its electrical conductivity, as shown in Figure 2 (Garrick et al. 2002).



Garrick et al. 2002, New England Transportation Consortium

Figure 2. Schematic illustration of the heater on a portable salinity detection device

Figure 3 presents the conductivity readings for eight runs during a snowstorm on March 3, 2001.



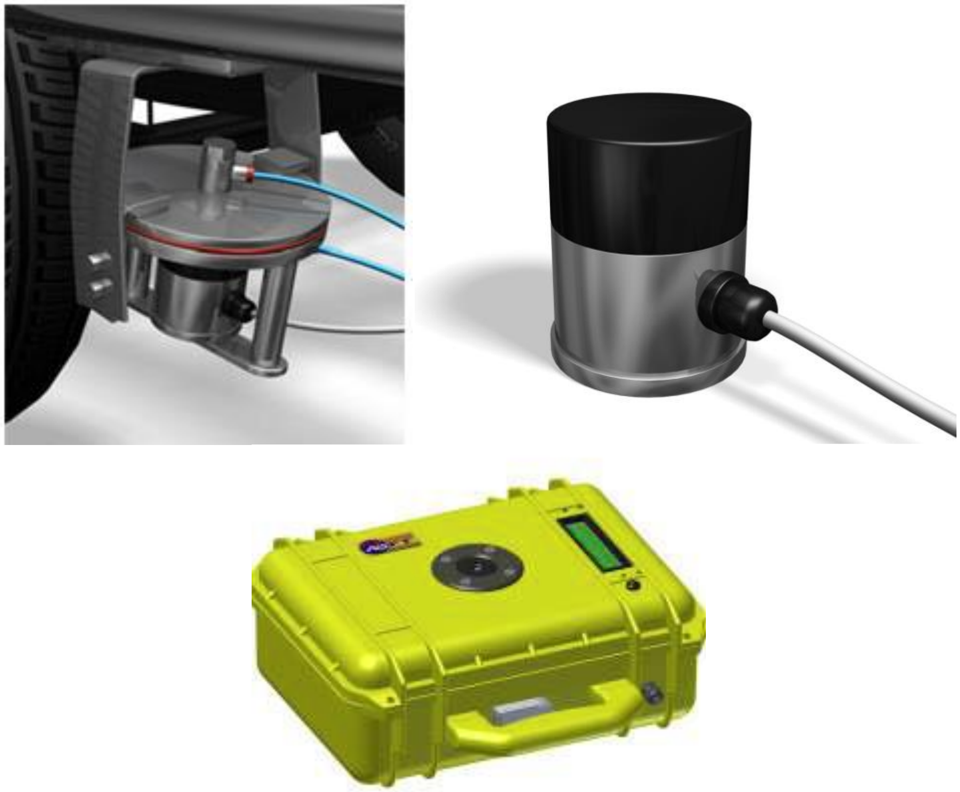
Garrick et al. 2002, New England Transportation Consortium

Figure 3. Conductivity readings from salinity measurements on eight runs during a snowstorm

Field tests showed that the sensor is easy to install and properly reflects the salinity concentration on pavement surfaces. However, the accumulation of entrained sand in the box limited the fluid flowing into the collection box after a period of time (Garrick et al. 2002). This sensor only works in environments where tire splash can reach the sensor, and therefore it does not work on dry road surfaces and may require improvement to address the clogging issues caused by abrasives.

Freezing Point Detection

The Frensor sensor, made by American Safety Technologies, has a freezing point surveillance system that measures air and pavement temperature and road surface parameters, including dry, wet, and wet but not frozen conditions; presence of dew and frost; freezing point of liquid on the pavement surface; and friction (American Safety Technologies 2012). This system can be fixed in the pavement, installed on a vehicle as a mobile sensor, or used as a portable measurement instrument, as shown in Figure 4.



Top row: American Safety Technologies 2012, © ASTEQUIPMENT.COM 2012
Bottom: American Safety Technologies n.d.

Figure 4. Three different versions of Frensor sensors: mobile (vehicle-mounted) Frensor sensor (top left), fixed Frensor sensor (top right), portable Frensor sensor (bottom)

The Frensor sensor works by collecting vehicle splash from the pavement surface and measuring the freezing point of the liquid compared to water. This sensor does not directly measure salinity; instead, the sensor actively measures the freezing point of the liquid on the pavement surface. The freezing point at the head of the sensor is determined using a thermoelectric element, which measures current through a series of heating and cooling cycles and converts this to the temperature of the solution. The Frensor system uses the measured pavement surface temperature and the freezing point of the liquid on the pavement surface to calculate the delta temperature (Δ temp), or the difference between the two values. A larger the Δ temp value, or the larger the difference between the pavement surface temperature and the freezing point of the liquid on the surface, the less danger there is of ice formation on the pavement surface. A low Δ temp value means that ice may form soon and application of de-icing product should be considered. The Frensor sensor can only take measurements of collected liquid and does not report Δ temp values for dry surfaces.

Frensor sensors have been extensively field tested, and the technology is in its fifth generation of development. The manufacturer claims that this system is more accurate and reliable than other detection systems (ASFT n.d.). The sensors typically take 10 to 30 seconds to report a value, and a range of 3 seconds to as much as several minutes may be needed to detect and report a value, depending on the environmental conditions. The manufacturer reports that the mobile version is faster at detection and reporting values. Some other key features of the Frensor sensors are shown in Table 1.

Table 1. Key features of Frensor sensors

De-icing fluid	Detects freezing point for any de-icing fluid (e.g., NaCl, $CaCl_2$, Urea, Clearway, Safeway)
Road status reporting	Dry, wet, freezing point
Freezing point temperature detection range	-20 to 0 ºC (-4 to 32 °F)
Accuracy	± 0.7 ºC
Measurement temperature limits	-40 to 10 ºC (-40 to 50 °F), sensors will be in standby when environment temperature is too hot (above 10 ºC) or too cold (below -40 ºC)
Freezing and environment temperature condition to get freezing points	< 20 ºC (68 °F)
Detection time	Typically, 10 to 30 seconds. 3 seconds up to several minutes may be needed depending on the environmental conditions. The mobile version is faster.
Logging	10-minute values can be stored up to 3 months in flash memory
Power requirements	12 VDC, 3.5 A, or 230 VAC
Size	∅ 40 mm (1.5 in), height 40 mm (1.5 in)
Type	Cu sensor body, weight approx. 300 g each

The estimated cost for a vehicle-mounted mobile Frensor sensor, with installation and an in-vehicle computer, ranges from $70,000 to $75,000. This includes two Frensor freezing point sensors mounted behind each rear wheel, an in-vehicle control box, a temperature sensor, a touch screen computer for the operator, GPS and GPRS or real-time remote monitoring, and installation and training. The user interface is a 10.5-inch touch screen that shows vehicle location in real time and color codes data points of Δ temp on the map. The system allows for warning levels to be set in the color-coded system, with thresholds for color coding and warning levels set by the user. The data can be viewed remotely and archived for viewing later. The data can be viewed on the user interface in real time in graphical, tabular, and in-map display formats. The use of the map display requires GPS technology.

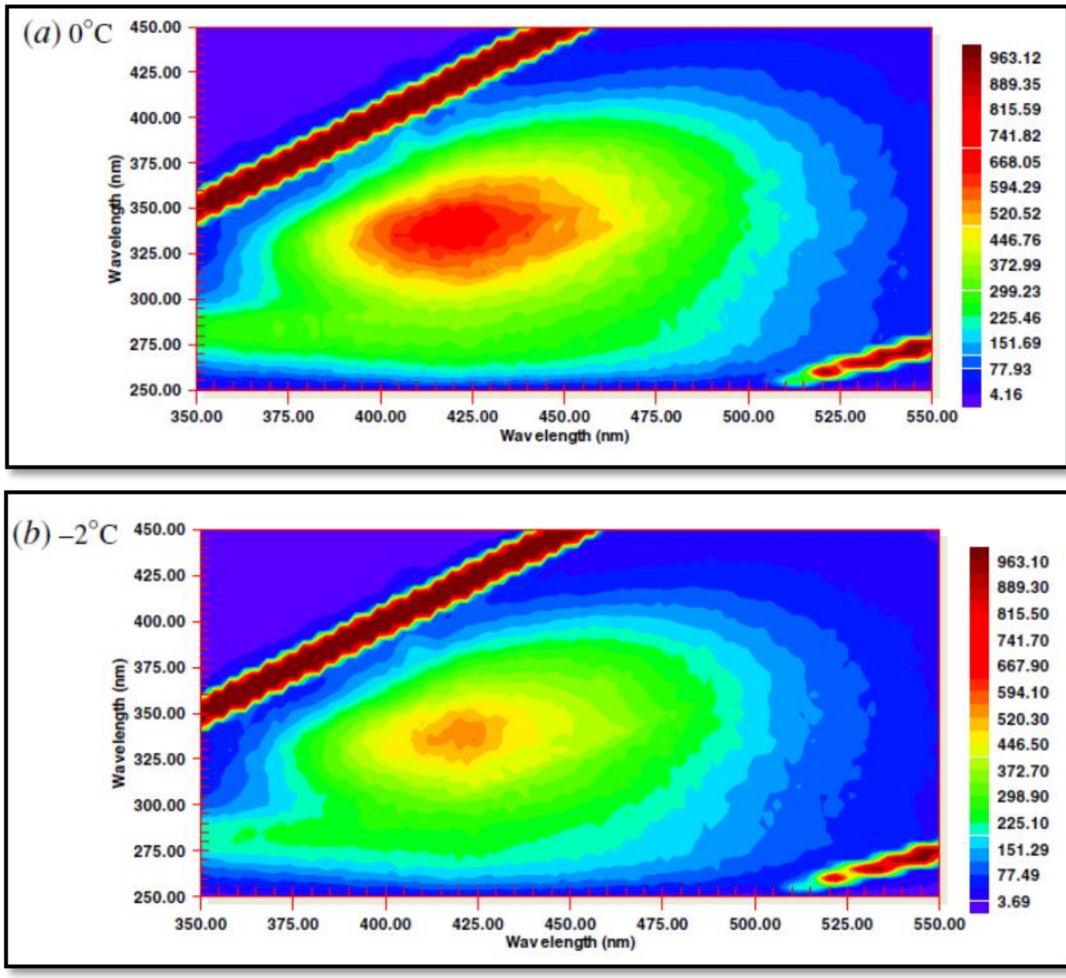
This sensor will only work in environments where tire splash can reach the sensor and therefore will not work on a dry road surface.

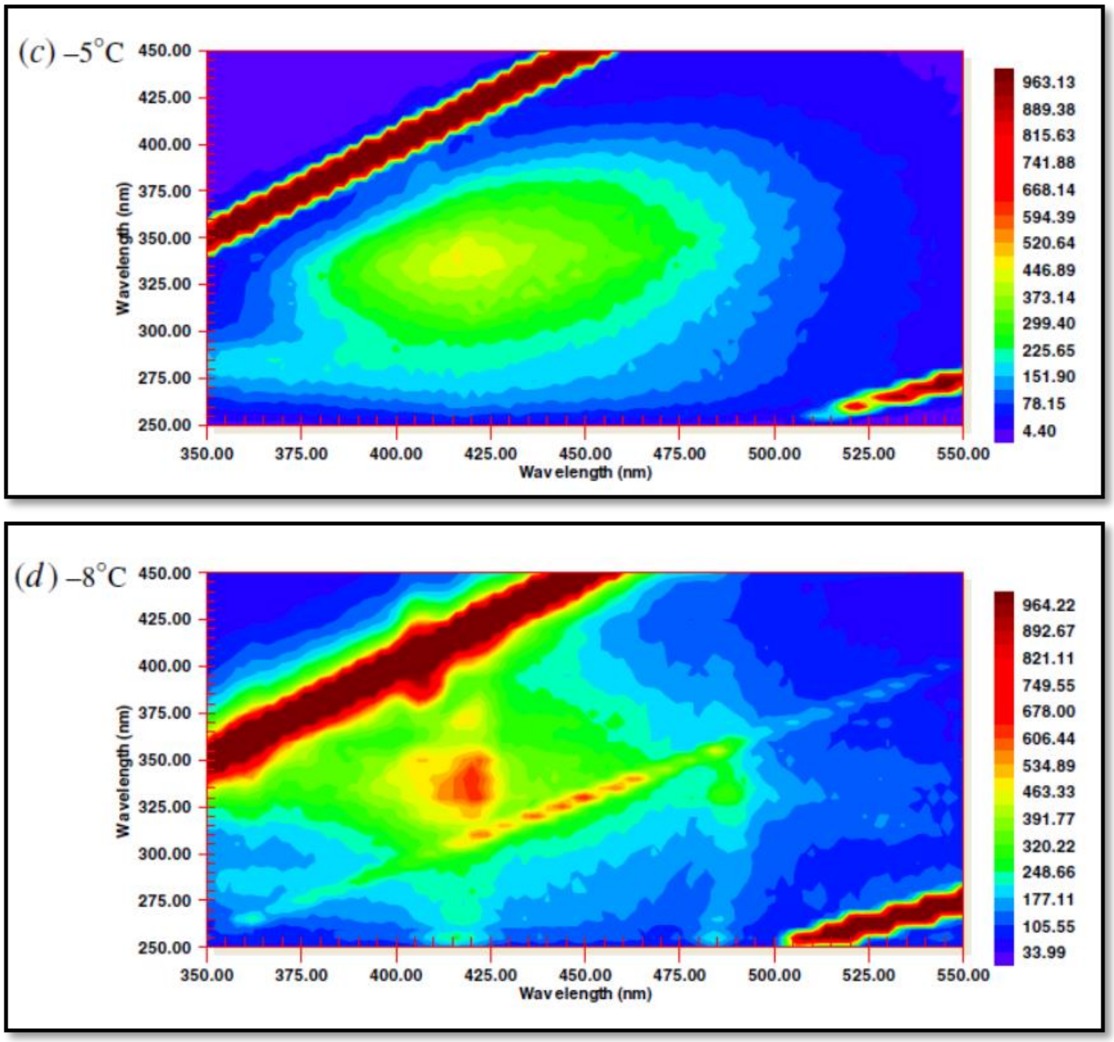
Optical Technology

Fluorescence Technology

A technology was developed to assess the salt concentration on pavement using the refractive index of the aqueous solution. In laboratory testing conducted in the United Kingdom, Hammond et al. (2007) used fluorescence technology to monitor residual salt concentration. The device used in the study directly measured salt concentration using fluorescence. Fluorescence occurs when a molecule absorbs photons from the ultraviolet-visible light spectrum (between 200 and 900 nm), which causes the molecule to transition to a high-energy electron state (excitation) and then emit photons as it returns to the its initial state (emission). For the molasses-based de-icing products mixed with salt that were tested, the peak intensity of the fluorescence excitation wavelength was about 340 nm, and the emission wavelength was about 420 nm. The excitation and emission wavelengths are unique signatures for each molecule and can be used to determine the presence and concentration of that molecule. These values are not affected by temperature. The fluorescence signal was readily detected as low as -8ºC (17.6°F), and the intensity of the signal was relatively stable at a temperature range of 0ºC to 5ºC (32°F to 41°F). Note that temperatures during winter maintenance operations are frequently below the reported stable detection temperature range for this device.

Figure 5 shows the excitation-emission matrices, or the graphical display of the fluorescence data, collected at 0°C, -2°C, -5°C, and -8°C (32°F, 28.4°F, 23°F, and 17.6°F), respectively. In the matrices, the larger the value on the right or the closer the color is to red, the higher the concentration of the detected product. The device was tested on dry surfaces, but the data collected were not reliable.


(a) 0°C
(b) −2°C
Wavelength (nm)
Wav elength (nm)
963.12
889.35
815.59
741.82
668.05
594.29
520.52
446.76
372.99
299.23
225.46
151.69
77.93
4.16
963.10
889.30
815.50
741.70
667.90
594.10
520.30
446.50
372.70
298.90
225.10
151.29
77.49
3.69



Hammond et al. 2007, © 2007 IOP Publishing, Ltd

Figure 5. Excitation–emission matrices for diluted salt at a temperature range between 0ºC and -8ºC (32°F to 17.6°F)

Efforts have been made to contact the authors of Hammond et al. (2007) through Campbell Scientific, where the authors are now employed in Australia. At this point in time, Campbell Scientific has no plans to further develop this technology. We are waiting to see if the authors have any additional input on this matter. Further development efforts could potentially make this sensor ready for field testing in the US during the winter of 2016–2017.

Similar to the device based on the fluorescence method, a remote optical salinity sensor was developed by Ruiz-Llata et al. (2014b) to monitor the residual salt concentration on roads. The working mechanism of the sensor utilizes an optical head, which has a light emitter, to produce fluorescence, and an optical receiver detects the signal. In the study by Ruiz-Llata et al. (2014b), the luminance properties of different salt samples were studied to evaluate the feasibility of the sensor system according to the natural fluorescence of various salts on wet and dry pavements.

Figure 6 is an image of the developed sensor system.

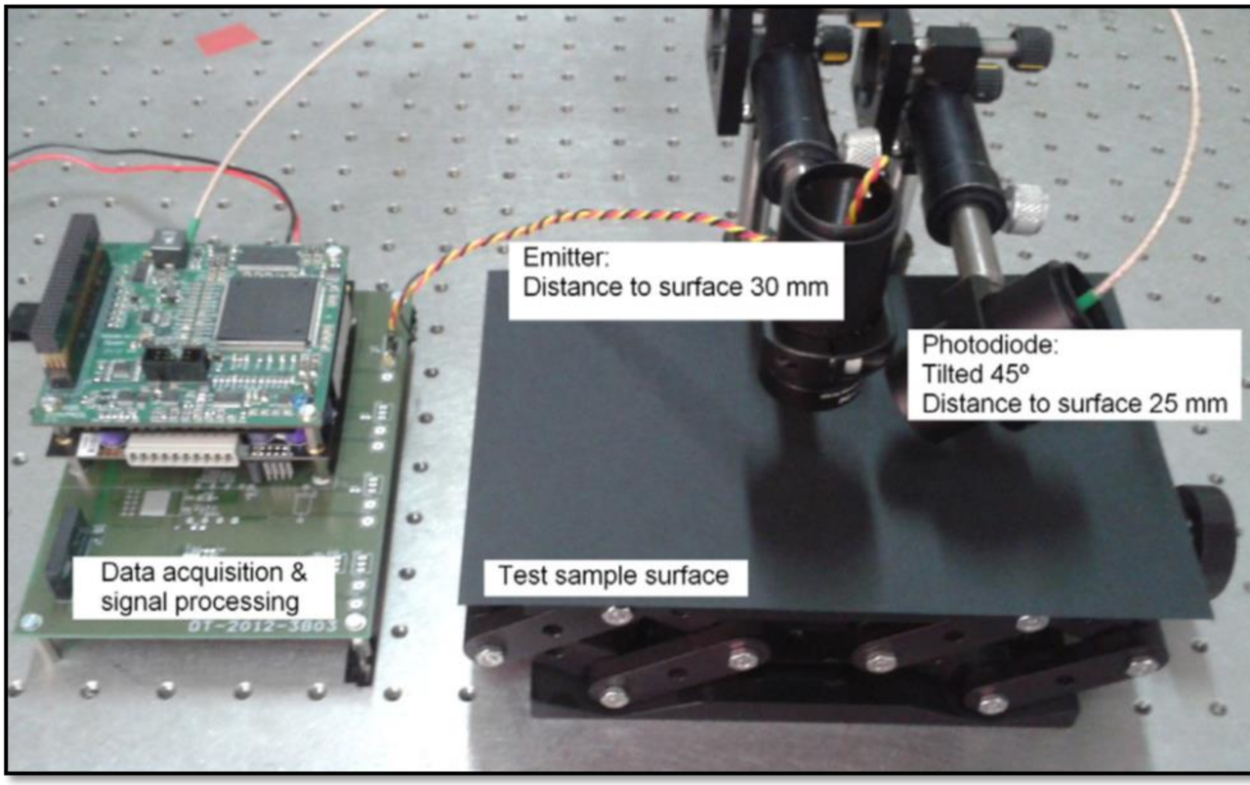
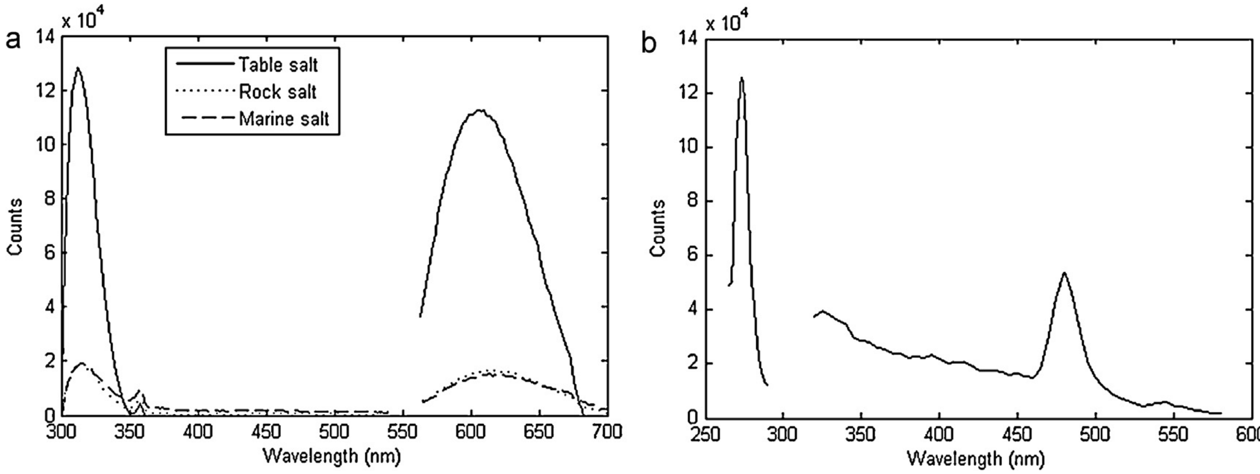


Figure 6. Remote optical sensors for real-time residual salt monitoring on road surfaces

The right-hand side of the image shows the tube mount and the LED holder with an ultraviolet filter in the vertical position. The tube mount and the holder were tilted 45 degrees from the photodiode and the attached red filter. The samples were placed on a stage that can be elevated to guarantee a constant distance to the target surface. The left-hand side of the figure shows the sensor's electronics, which include three printed circuit boards. The bottom board contains the analogue circuits with the LED driver and photodiode amplifier. The middle board is the power supply, and the top board includes the digital-to-analogue and analogue-to-digital converters, auxiliary circuits, and the field programmable gate array.

Figure 7 shows the resulting emission spectrums with an excitation wavelength of 273 nm for different salts.



Reprinted from Ruiz-Llata et al. 2014b with permission from Elsevier © 2013

Figure 7. Fluorescence characteristic peaks for various salts: Emission spectrum with excitation at a wavelength of 273 nm (left) and excitation spectrum measured at an emission wavelength of 610 nm (right)

In the left-hand chart, the emission peaks at 310 nm and 610 nm (table salt) are clearly identified. As shown in the right-hand chart, the maximum excitation can be observed in the ultraviolet range, with an absorption peak at 273 nm. The laboratory test results show that the sensor has a measurement error of 10%, which includes the effects of temperature, when detecting a maximum salt concentration of typical anti-icing (or de-icing) road treatments (20 g/m^2, 4.2 lbs. per 1000 ft^2, or approximately 265 lbs/l-m). This sensor directly measures salinity on wet and dry surfaces.

The sensor has only been developed to the laboratory prototype phase. The researchers are planning for the development of a preproduction device that could be ready for field trials in one year (M. Ruiz-Llata, personal communication, March 3, 2015). This device will likely not be ready for field testing in the US during the winter of 2015–2016. For this reason, we recommend that this device be tested in Phase II field trials in the winter of 2016–2017.

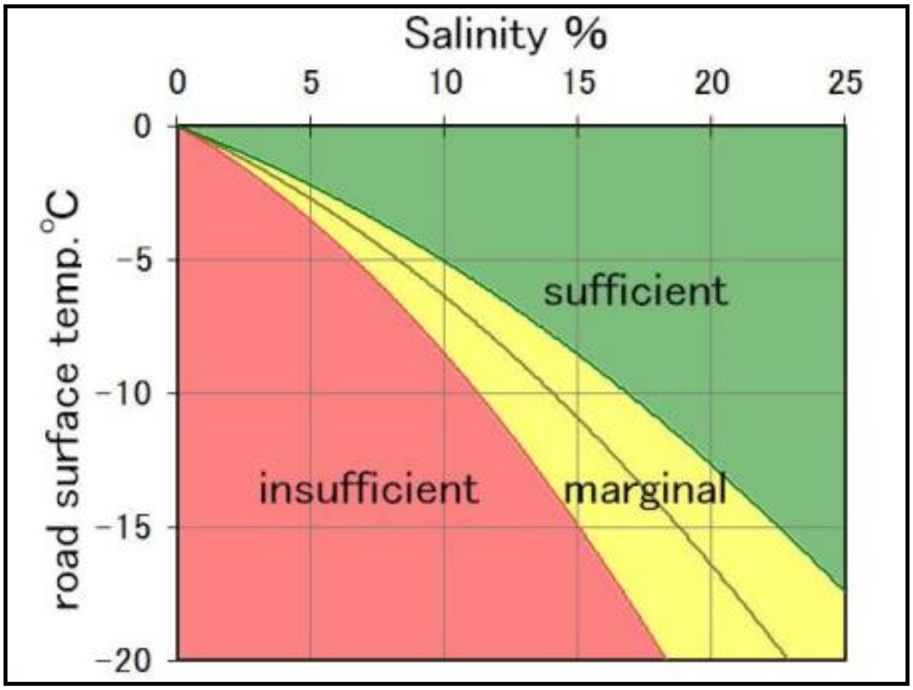
Refractive Index

The Yamada-Giken mobile salinity sensor uses optical refractometer technology to measure the freezing point of surface moisture based on tire splash and provides information on the salt concentration on the pavement surface (Smithson 2012, Suya 2014) (Figure 8).

Suya 2014

Figure 8. The installation of Yamada-Giken mobile salinity sensor

The sensor optically measures salinity from tire splash. The device also measures air and pavement temperature and reports calculated salt concentration for defreezing (%), suggested road surface temperature for freezing (°C), and road condition. The salinity and road surface temperature data are applied to a NaCl solution state diagram, shown in Figure 9, to provide an estimation of surface condition in terms of sufficient, marginal, or insufficient salt. The surface condition is color coded and shown graphically and on a map in the user interface. However, because output data for this calculation are based on the NaCl solution state diagram, the calculation only works where NaCl-based salt is used.



Suya 2014

Figure 9. NaCl solution state diagram

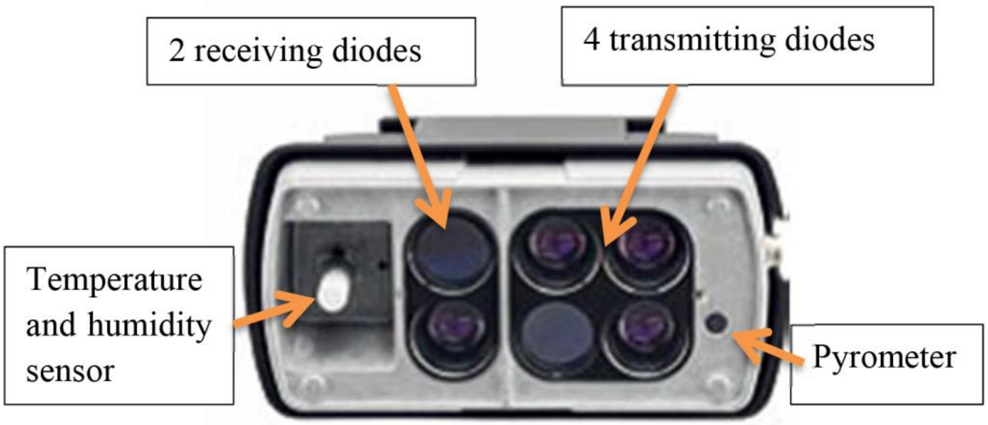
The system uses GPS technology to track vehicle location and a telecommunication antenna to relay data every five seconds to a computer for remote viewing and to an in-vehicle display. The system uses a road surface temperature sensor and a salinity measurement sensor. Data are shown on an in-vehicle display and can be viewed remotely. Future work to further implement the data collected by this device includes the use of a guidance salinity control diagram, where the measured road surface temperature and salinity are used to determine the approximate amount of salt that needs to be applied to the road surface to maintain a standard salting rate (Suya 2014).

This sensor has been extensively field tested and used in Japan on expressways for over eight years. Past attempts (winter of 2011–2012) to test this sensor in the US did not occur due to the timing of the winter and cost issues (related to the strength of the Japanese yen to the US dollar) (Y. Suya, personal communication, March 2015). The cost to purchase this sensor with the user interface ranges from $1,500 (refurbished, no warranty) to $5,400 (new, five-year warranty). (The manufacturer offered a 20% discount on new sensors purchased for use in this project. Costs did not include shipping from Japan.) This sensor only works in an environment where tire splash can reach the sensor, and therefore it does not work on a dry road surface.

Infrared Measurement

The Lufft Mobile Advanced Road Weather Information Sensor (MARWIS-UMB) measures road surface temperature, water film height, dew point temperature, road condition (including dry, moist, wet, snow, or ice), chemically wet condition, ice percentage, friction, and relative humidity above the road surface. Currently, the MARWIS-UMB system does not provide data on the salt concentration present on the pavement surface. At this time, the MARWIS-UMB system reports whether the road surface is chemically wet. Lufft is working to modify this reading to report salt concentration on the pavement surface.

The MARWIS-UMB sensor works using infrared measuring, with four emitting and two receiving diodes that capture the reflecting behavior of the road surface at varying wavelengths (Lufft n.d.) (Figure 10).



Lufft n.d., © MARWIS 2015

Figure 10. MARWIS-UMB components

The different spectral properties of substances on the road (water, ice, etc.) can be determined from the captured values. Road surface temperature is measured using a non-invasive pyrometer, and relative humidity is measured. Water film height is measured using a non-invasive optical spectroscopy sensor (emitting and receiving diodes). Ice percentage is determined using optical spectroscopy (emitting and receiving diodes), where the frozen part of the aqueous solution on the road surface is determined and a percentage is calculated. Road condition is determined using the measured water film height and road surface temperature and ice percentage values; from these measurements, the sensor reports whether the road is dry, damp, wet, snowy/icy, or chemically wet.

The Lufft MARWIS-UMB sensors are mounted on trucks or cars using a rack or or magnet, have a protective cover, and are mounted with a distance of 1 or 2 m (3.2 to 6.5 ft) between the measuring instrument and the object of measurement. The information is displayed in the vehicle on an iPad mini (or iPhone), which shows the information in various formats. The information is sent using Bluetooth technology and does not require the vehicle to have an onboard GPS. The software features a map that shows road conditions, which can be color coded to show ice, dry pavement, rain, etc. In addition to this information, air and pavement surface temperature and water height are shown. An alert system can be set up for parameter thresholds based on the user's needs. Data from multiple sensor can be viewed on one screen (with up to six unique profiles per iPad) or separate screens. Additional historical data can be viewed. The MARWIS-UMB system has a list price of $5,300. Lufft is offering free three-month trials.

Figure 11 shows the MARWIS-UMB sensor mounted on a vehicle.

Lufft 2014

Figure 11. MARWIS-UMB 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, using the collected data. Some key features of the Lufft MARWIS-UMB are shown in Table 2.

Table 2. Key features of Lufft MARWIS-UMB

Size	Dimensions	Height - 110 mm, Width - 200 mm, Diameter - 100 mm
	Weight	1.7 kg
Storage conditions	Permissible ambient temp.	-40ºC to 70ºC (-40°F to 158°F)
	Permissible relative humidity	< 95% relative humidity, non-condensing
Operating conditions	Operating voltage	10 to 28 VDC, approx. 3VA w/o heating, 50VA w/ heating
	Permissible operating temp.	-40ºC to 60ºC (-40°F to 140°F)
Dew point temperature	Measuring range	-50ºC to 60ºC (-58°F to 140°F)
	Accuracy	± 1.5ºC (from 0ºC to 35ºC)
Water film height	Measuring range	0 to 6000 µm
	Resolution	0.1 µm
Road surface temperature	Principle	Pyrometer (none contact infrared thermometer)
	Measuring range	-40ºC to 70ºC (-40°F to 158°F)
	Accuracy	± 0.8ºC at 0ºC
	Resolution	0.1ºC
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-UMB system is commercially available and is being field testing in many states and countries, but at this time it does report salinity values. A procedure for converting the chemically wet parameter to report salinity or product concentration on the pavement surface is still under development. For this reason, the device will not be ready for salinity testing during the winter of 2015–2016. Instead, we recommend this device for testing in Phase II field trials in the winter of 2016–2017. We recommend working with this manufacturer to ensure that future salinity data can be captured from wet and dry pavements.

Correlation with Surrogate Data - Friction

The Teconer RCM411 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 and ice thickness; and coefficient of friction (Teconer, Ltd. 2015) (Figure 12).

Figure 12. Teconer RCM411 mounted on the rear bumper of passenger vehicle

The RCM411 is an optical remote sensor based on spectral analysis that measures optical reflection signals from the road surface. The system then analyzes the data to produce a road surface condition and friction report. The purchase costs of a new RCM411 is around $9,000.

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). This newer sensor does not directly measure salinity on the road surface. While still under development and not commercially available, Teconer is willing to make this product available for research and field testing purposes (T. Haavasoja, personal communication, March 2015). Teconer is still unsure whether this product will be a revised version of the RCM411 or a separate technology altogether.

The calculation method for brine fraction (salt concentration) does not work at warmer temperatures (e.g., well above freezing) and when friction values are not changing. In most cases, this method will not work when the road surface is dry because friction values are not changing. Teconer reports an error rate of about 3% for NaCl content 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 the working parameters and functional capabilities of the RCM411 sensor is provided in Table 3.

Table 3. 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.	-40ºC to 70ºC (-40ºF 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.	-20ºC to 50ºC (-4ºF 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

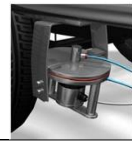
Source: Teconer, Ltd. 2015

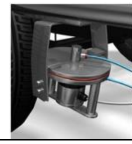
CONCLUSIONS AND RECOMMENDATIONS

Winter maintenance operations typically involve the application of salts to roadways to combat the formation of ice or snow pack on the road surface. However, precise knowledge of pavement conditions, specifically the amount of salt remaining on the pavement surface, is needed for making decisions about chemical applications to maximize the benefits and reduce the negative effects of road salt usage in maintenance operations. Salinity sensing technologies are effective solutions to meet such needs.

Three types of salinity sensors are available for measuring the salinity of the road surface: in-pavement sensors, portable sensors, and vehicle-mounted sensors. Information on in-pavement and portable salinity sensors can be found in Appendix B. The focus of this phase of the research was to report on available mobile salinity measurement technologies. Seven mobile salinity sensors were identified as potential candidates for Phase II field trials. Table 4 summarizes these sensors' physical properties, sampling characteristics, lag times, data collection limitations, reliability and error rates, maturity of development, and, if available, user interface.

Table 4. Summary of vehicle-mounted salinity sensor properties

Sensor name	Garrick 2002 	Frensor 	Hammond et al. 2007	Ruiz-Llata et al. 2014	Yamada-Giken 	Lufft MARWIS 	Teconer 
Detection Method	Electrical Conductance	Freezing Point Detection	Refractive Index/Fluorescence Technology	Refractive Index/Fluorescence Technology	Refractive Index	Infrared Measurement	Correlation with surrogate data - Friction
Directly measures NaCl	Yes	No	Yes	Yes	Yes	No	No
Wet/Dry Reading	Wet only	Wet only	Wet/dry(not well detected)	Wet/Dry	Wet only	Wet only (at this time)	Wet only
Tested parameters	Salt, salt-sand.	Detects freezing point for any de-icing fluid (e.g., NaCl, $CaCl_2$, Urea, Clearway, Safeway etc.)	Used a fiber optic probe. Tested on a molasses based deicer mix.	Tested on various salts.	Correlates road temperature with salt solution state diagram to provide surface condition information.	Tested on many pavement types.	Field tested.
Sampling characteristics	Collects tire splash off the road surface.	Collects tire splash off the road surface.	No physical sample required, non-invasive, utilizes optical technology.	No physical sample required, non-invasive, utilizes optical technology.	Collects a reading from tire splash.	No physical sample required, non-invasive, utilizes optical technology.	No physical sample required, non-invasive, utilizes optical technology.
Data collection - lag time		10 - 30 sec (3 sec - several minutes)					

Sensor name	**Garrick 2002** 	**Frensor** 	**Hammond et al. 2007**	**Ruiz-Llata et al. 2014**	**Yamada-Giken** 	**Lufft MARWIS** 	**Teconer** 
Data collection - limitation	Only collects data when tire splash from the road surface can be collected. Clogging issues did occur from abrasives in tire splash.	Only collects data when tire splash from the road surface can be collected.	Fluorescence signal detection and stability range of 32° to 41°F. May not perform well at colder temps typical during winter maintenance operations, or working temp range for chloride based products (15° to 32°F).	No field testing conducted.	Only collects data when tire splash from the road surface can be collected. Surface condition information only applies where NaCl is used.	Currently only reports chemically wet road surfaces.	Issues associated with the brine fraction (salt concentration) calculation method occur at temps above freezing and when friction values are not changing, such that the calculation method does not work.
Error Rate				10%		±0.8 at 0°C	3%
Maturity of Development	Fully developed and tested field prototype.	Fully developed and field tested commercially available product.	Developed and tested lab prototype. Dry surface data were not strong enough to produce a value.	Developed and tested lab prototype. Working this next year to develop a field prototype.	Fully developed and field tested commercially available product.	Does not report salinity at this time. Other parameters are fully developed and field, tested commercially available product.	The calculation method is fully developed and field tested, but is not currently linked with a sensor or user interface.

Sensor name	Garrick 2002 	Frensor 	Hammond et al. 2007	Ruiz-Llata et al. 2014	Yamada-Giken 	Lufft MARWIS 	Teconer 
User Interface	None	The data is reported real time in graphical, tabular, map display in the vehicle on a computer screen. The use of the map display requires GPS. The system allows for remote viewing of the data.	None	None	The system uses GPS technology to track the vehicle location, and a telecom antenna to relay data every 5 seconds to a computer for remote viewing, as well as on an in-vehicle display.	The in-vehicle user interface is an iPad mini with a user interface program. Data from up to six separate sensors can be viewed on one user interface at a time. Remote viewing of data capable.	None
Cost Estimate	NA	$70,000 - $75,000	NA	NA	$1,500–$5,400 (does not include shipping from Japan)	$5,300, offering free 3 month field trial	$9,000 for the sensor, no cost for the calculation method
Recommended for Field Trials	**No**	**No**	**No**	**Yes, Phase II (2016–2017)**	**No**	**Yes, Phase II (2016–2017)**	**No**

The advantages of using vehicle-mounted salinity sensors include the continuous measurement of salinity, increased efficiency and therefore less time spent on data collection and the use of data to make application decisions, and the ability to take measurements while plowing, on patrol, etc. The disadvantages of using vehicle-mounted salinity sensors include their higher relative cost compared other types of salinity sensors and the fact that, generally, the sensors only sample in a single line on the road (i.e., the wheel path).

The following recommendations can be made based on the findings of the literature review, survey, and follow up interviews.

Phase II Field Testing Recommendations

Both the Ruiz-Llata and Lufft MARWIS-UMB mobile salinity sensors show a lot of promise as mobile vehicle-mounted salinity sensors. Unfortunately, however, these technologies require at least one or more years of development before they are ready for field trails. For this reason, we recommend that these technologies be considered for testing during the winter of 2016–2017. To ensure that these technologies are ready for field testing during the winter of 2016–2017, we suggest that the Aurora technical team and the researchers communicate this plan to Marta Ruiz-Llata and Lufft.

One consideration for the Phase II field trials is the side-by-side comparison of a mobile salinity sensor that directly measures residual chloride on the road surface and that is still in development, e.g., Garrick et al. (2002) or Ruiz-Llata et al. (2014b), with a sensor that indirectly measures salinity on the road surface but that is fully developed, e.g., Frensor, Yamada-Giken, or Teconer.

Phase III Blended Product Detection Using Mobile Salinity Sensing Technology

The use of blended products in winter maintenance operations is becoming more common; in fact, it is standard practice in many places. Blended products may be a mixture of liquid chlorides, liquid and solid chlorides, chlorides with agriculturally derived products, or non-chloride-based products. It is important to ensure that the technology that is being invested in by transportation agencies is able to grow or be easily modified to accommodate changing practices and de-icing materials used. For this reason, we suggest testing the most viable mobile salinity sensing technologies for their ability to detect and determine salinity concentrations on road surfaces where blended products are used.

REFERENCES

American Safety Technologies. 2012. *Active Freezing Point Sensor— Frensor*. http://www.astequipment.com/13-0-FRENSOR.html. Last accessed May 2015.

American Safety Technologies. n.d. *Frensor: Active freezing point surveillance by ASFT*. American Safety Technologies, Pepperell, MA, and ASFT, Köpingebro, Sweden. http://www.astequipment.com/files/frensor-brochure.pdf. Last accessed May 2015.

ASFT. n.d. *The Active Road and Runway Condition Sensor - Frensor MKII*. Airport Surface Friction Tester (AFST) Industries AB, Köpingebro, Sweden. http://www.asft.se/upl/files/116731.pdf. Last accessed May 2015.

Highways Agency. 2007. SSR National Framework Contract Task 191 (387) ATK, Residual De-Icing Salt Levels, Technology Review of Measurement Techniques for Residual Salinity. Guildford, UK.

Bridge, P. 2008. Noninvasive Road Weather Sensors. *TRB Transportation Research Circular E-C126: Surface Transportation Weather and Snow Removal and Ice Control Technology*. Transportation Research Board, pp. 407–415.

Cai, L., B. Li, and C. Meng. 2014. Study on standardized testing methodologies for embedded pavement status sensors. Paper presented at the 2014 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI), October 8–10, New York, NY.

Fleege, E.J., B. Scott, E. Minge, M. Gallagher, J. Sabie, S. Petersen, C. Kruse, C. Han, D. Larson, and E.O. Lukanen. 2006. *NCHRP Web-Only Document 87, Project 6-15: Test Methods for Evaluating Field Performance of RWIS Sensors*. National Cooperative Highway Research Program, Washington, DC.

Garrick, N. W., N. P. Nikolaidis, and J. Luo. 2002. *A Portable Method to Determine Chloride Concentration on Roadway Pavements*. New England Transportation Consortium, University of Connecticut, Storrs, CT.

Haavasoja, T. 2015. Freezing of Salty Solutions vs Mobile Surface Condition and Friction Measurements. Presentation at PIARC TC 2.4 Workshop, March 11, Helsinki, Finland.

Hammond, D. S., L. Chapman, A. Baker, J. E. Thornes, and A. Sandford. 2007. Fluorescence of road salt additives: potential applications for residual salt monitoring. *Measurement Science and Technology*, Vol. 18, No. 1, p. 239–244.

Hussain, G. and I. A. Al-Hawas. 2008. Salinity sensor: A reliable tool for monitoring in situ soil salinity under saline irrigation. *International Journal of Soil Science*, Vol. 3, No. 2, pp. 92–100.

Lufft. n.d. Mobile Collection of Weather Data in Real Time with MARWIS. MARWIS. http://lufft-marwis.com/en_US/features. Last accessed May 2015.

Lufft. 2014. *Lufft MARWIS-UMB: Mobile Advanced Road Weather Information Sensor*. http://www.windup.pt/resources/MARWIS_09_2014.pdf. Last accessed May 2015.

Lysbakken, K. R. and A. Lalague. 2013. Accuracy of SOBO 20 in the Measurement of Salt on Winter Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, No. 2329, pp. 24–30.

M. H. Corbin, LLC. n.d. *VX Pavement Sensor*. http://www.mhcorbin.com/products/manufactured-products/vx-pavement-sensor. Last accessed May 2015. Current link to VX sensor, http://www.mhcorbin.com/vx21-road-sensor/.

Nygaard, H. 2005. *Rapport Restsaltmåleren SOBO 20*. Vinterudvalget, Denmark.
Rahman, H. A., S. W. Harun, M. Yasin, S. W. Phang, S. S. A. Damanhuri, H. Arof, and H. Ahmad. 2011. Tapered plastic multimode fiber sensor for salinity detection. *Sensors and Actuators A: Physical*, Vol. 171, No. 2, pp. 219–222.
Ruiz-Llata, M., P. Martin-Mateos, G. Guarnizo, and P. Acedo. 2014a. Advances in Laser and Optical Technologies for Road State Detection Applications. Paper presented at PIARC 14th International World Roads Congress, February 4–7, Andorra la Vella, Andorra.
Ruiz-Llata, M., P. Martin-Mateos, J. R. Lopez, and P. Acedo. 2014b. Remote optical sensor for real-time residual salt monitoring on road surfaces. *Sensors and Actuators B: Chemical*, Vol. 191, pp. 371–376.
Sherif, A. and Y. Hassan. 2004. Modelling pavement temperature for winter maintenance operations. *Canadian Journal of Civil Engineering*, Vol. 31, No. 2, pp. 369–378.
Smithson, L. 2012. *The Evolution of Optimized and Sustainable Pro-Active Winter Operations*. http://www.sirwec2012.fi/Extended_Abstracts/016_Smithson.pdf. Last accessed May 2015.
Strong, C. and L. Fay. 2007. *RWIS Usage Report*. Alaska Department of Transportation and Public Facilities, Juneau, AK.
Suya, Y. 2014. New road surface maintenance of expressway using an on-vehicle salinity sensor system which measures the salinity continuously. Paper presented at PIARC 14th International World Roads Congress, February 4–7, Andorra la Vella, Andorra. http://www.yamada-giken.co.jp/axf_user/files/oralpresentation_61ygSuya_rev1.pdf. Last accessed May 2015.
Teconer, Ltd. 2015. Winter maintenance of roads and runways. *RCM411*. http://www.teconer.fi/en/winter.html. Last accessed May 2015.
Turune, M. 1997. Measuring salt and freezing temperature on roads. *Meteorological Applications*, Vol. 4, pp. 11–15.
Ye, Z., X. Shi, C. K. Strong, and R. E. Larson. 2012. Vehicle-based sensor technologies for winter highway operations. *IET Intelligent Transportation Systems*, Vol 6, No. 3, pp. 336–345.

APPENDIX A. PRACTITIONER SURVEY RESULTS

A survey was distributed through the online survey tool Survey Monkey in February 2015 and was open for responses for one month. The purpose of this survey was to gather information from winter maintenance professionals at state, provincial, and local transportation agencies on their experience with salinity sensors used in winter snow and ice control operations to measure salt concentration on pavements. The survey consisted of 14 questions. A total of 50 people accessed the survey, but participants did not respond to every question. Detailed information about each question and the responses are provided below.

Q1: Please provide your contact information.

A total of 33 responses from 6 countries were received from Norway (n=1), Finland (n=1), Denmark (n=1), U.K. (n=1), Canada (n=4), and US (n=25), and 17 respondents skipped this question. The US respondents were from 17 states, including California (n=2), Colorado (n=1), Indiana (n=1), Iowa (n=3), Kansas (n=1), Massachusetts (n=1), Michigan (n=1), Minnesota (n=3), Montana (n=1), Nevada (n=1), New York (n=1), North Dakota (n=2), Ohio (n=1), Pennsylvania (n=2), Utah (n=2), West Virginia (n=1), and Wisconsin (n=1) (Figure 13).

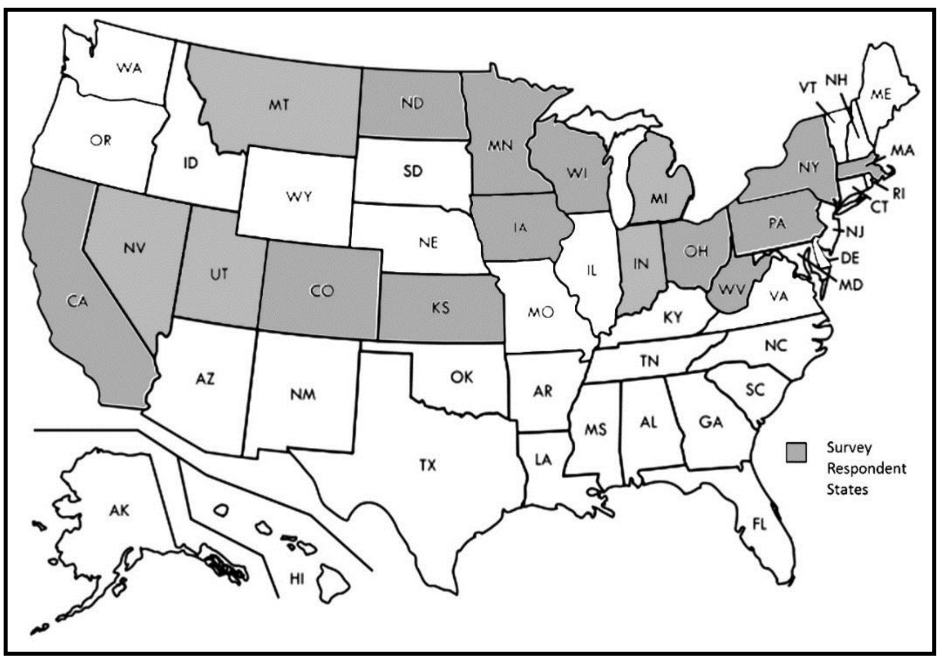


Figure 13. US states with survey respondents

Survey respondents were mainly from “State or Province” winter maintenance agencies (68.75%), with a smaller percentage from the “Company” (36.36%) category. There were also a few other respondents from the “University” (9.09%) category. Specific response counts and percentages for each agency type are presented in Table 5.

Table 5. Number of responses for each agency type.

Agency Type	Response Percent	Response Count
State or province winter maintenance agency	68.75%	22
University	9.09%	2
Company	36.36%	8
	Answered question	**32**
	Skipped question	**1**

Q2. Do you or your agency use salinity sensors in winter maintenance operations? (Salinity sensors are designed to measure the salt (or chloride) concentration on pavement.)

There were 50 responses collected for this question; 22 answered "Yes" and 28 marked "No," which implies that although salinity sensors are theoretically beneficial to the winter maintenance activities, efforts explaining the benefits of these sensors may help increase the use of these sensors and determine the reason for the limited use of salinity sensors. Responses are shown in Figure 14.

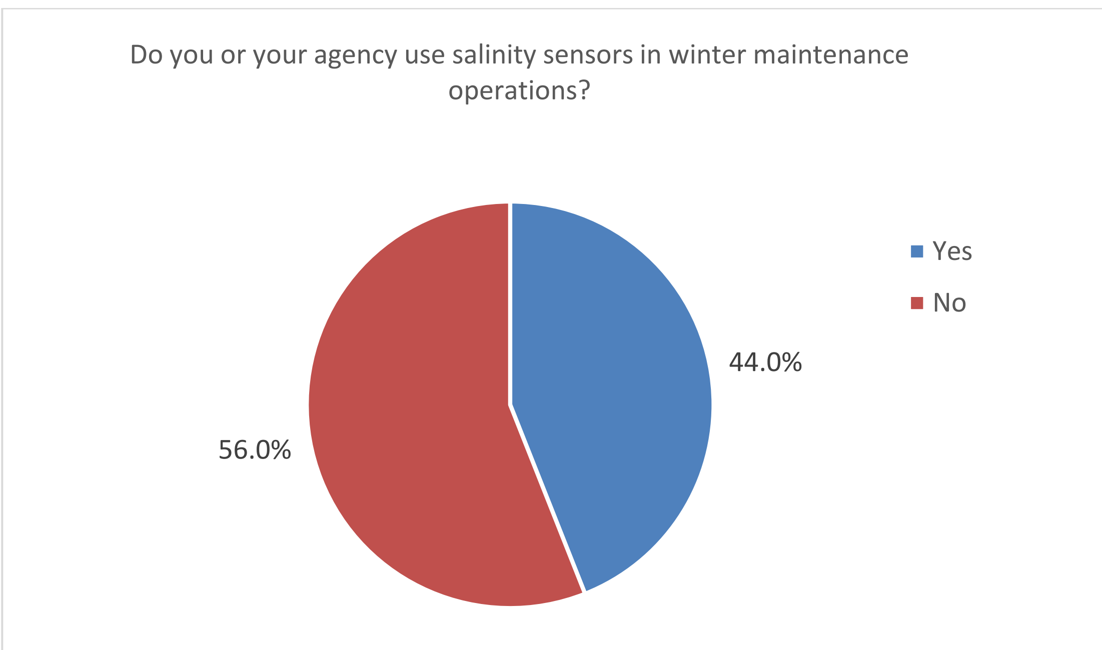


Figure 14. Survey responses for the use of salinity sensors in winter maintenance operations

Q3. If no, have you considered using salinity sensors? Please explain.

Among the 28 respondents that answered "No" in Q2, a total of 16 responded to this follow-up question. Comments provided by these respondents are shown in Table 6.

Table 6. Follow-up comments on the considerations of using salinity sensors

Agency	Comments
Iowa DOT	Yes, we have purchased some. We have Vaisala FP2000s, which are supposed to do salinity measurements but we don't trust the readings.
Nevada DOT	No, maintenance of devices is a challenge with our available resources. That’s not something we thought about yet.
North Dakota DOT	Not at this time
University of Birmingham	Personally not involved in operations.
Lufft USA Inc.	We are a manufacturer of RWIS sensors.
Pennsylvania DOT	Previously used with the RWIS network but the system is currently down for replacement.
	We’ve thought about it at a high level, but never moved on it. To our knowledge there are none sufficiently rugged enough to withstand the environment of a plow truck.
	Yes, on brine makers, but they have proved unreliable.
	No
Alberta Transportation	Our department is just getting into anti-icing, and have not needed to know residual chloride concentrations up to now.
Sustainable Salting Solutions, LLC	Yes. This could be one of the most important tools for winter maintenance after the pavement temp.
Minnesota DOT	Have no knowledge of them
Iowa DOT	We have not considered using these sensors. We are focusing our efforts in other areas such as updating our GPS/AVL system along with our regular temperature sensors on our snowplow trucks.
Minnesota DOT	Yes, we are interested in knowing existing salinity concentrations so as to adjust app rates.
	We don’t use salt.
	We have discussed but not in depth. Our salt brine program is still in the early stages.

Q4. If yes, what kind of salinity sensors do you use? (Please describe the salinity sensors you use, whether multiple from a category or from varying categories below.)

Among the 22 respondents that answered “Yes” in Q2, 12 provided follow-up responses to this question. In total, 9 responding agencies stated that they use “in-pavement sensors” (75%), 2 agencies reported the use “portable but not vehicle-mounted sensors” (16.7%), and 1 agency stated it uses “vehicle-mounted sensors” (8.3%). Detailed responses on the type of salinity sensors used by respondents are presented in Table 7.

Table 7. Salinity sensors used by survey respondents

Agency	In-pavement sensors	Portable but not vehicle-mounted sensors	Vehicle-mounted sensors
Minnesota DOT	Yes	Not used	Not used
New York DOT	Lufft IRS 31		
Teconer Ltd			Road Condition Monitor
North Dakota DOT	FP2000 and IRS31	None	None
Ohio DOT	VX-21-2 and some FP-2000		
Utah DOT	Lufft IRS21		
Kansas DOT	FP-2000, IRS3, Non-Invasive Pavement Sensor		
Wisconsin DOT	Vaisala		
Massachusetts DOT	Ground Hogs provided by Vaisala		
AIBAN Vinterservice		Salt stick	
Brun-Way Highways Operations	For RWIS Stations		
University of Waterloo		SOBO20	

Q5. For each salinity sensor you use please provide specific information such as manufacturer, model, purchase price, annual maintenance cost, typical service life, mounting location, etc.

Because this is a follow-up question from Q4, a total of 13 responses were collected for this question, including the 12 respondents of Q4 and an additional respondent from the Utah Department of Transportation. Specific information about the salinity sensors used is summarized in Table 8.

Table 8. Specific information of adopted salinity sensors

Type of Senor	Agency	Manufacturer	Model	Purchasing cost	Annual maintenance cost	Typical service life	Mounting location	Additional information (please specify)
In-pavement	Minnesota DOT	Vaisala	FP 2000	$3,100		3–10 years	Just outside of right wheel track	
	New York DOT	Lufft	IRS 31	$5,000+ each	Minimal	Guessing 10 years	In driving lane as per Lufft guidelines	IRS 31 no longer manufactured?
	North Dakota DOT	Vaisala, Lufft	FP2000, IRS31	Not sure, we don't buy them directly	$300	10 years	Just inside wheel path	
	Ohio DOT	MH Corbin / Vaisala	VX-21-2/ FP-2000	$1,387.00/ $5,581.16	$0.00/ $0.00	Unknown / Life cycle of pavement unless they are cut. The sensor is not removable.	Both are in the roadway or bridge decks	
	Utah DOT	Lufft	IRS21	$4,455	$1,078.49 per RWIS site (2014)	~ 3 years	1 ft into the lane just outside of the tire track.	
	Kansas DOT	Vaisala, Lufft	FP-2000, IRS31	$3,900, $5,468	None	10 years	In wheel path	
	Wisconsin DOT	Vaisala	FP2000	$4,000	Unknown		10 years	
	Massachusetts DOT	Vaisala				< 5 years		They were installed many years ago.
	Brun-Way Highways Operations					8 years	Fixed puck in the pavement	

Type of Senor	Agency	Manufacturer	Model	Purchasing cost	Annual maintenance cost	Typical service life	Mounting location	Additional information (please specify)
Portable (not vehicle-mounted)	University of Waterloo	Boschung	SOBO	$8,000 ($6,300 US)				We faced a lot of problems with this device (to be honest).
	AIBAN Vinterservice	Boschung	Sobo 20	50,000 kr DK ($7,300 US)	1,000 kr DK ($146 US)	20 years	More places across the road	
Vehicle-Mounted	Teconer Ltd	Teconer Ltd	RCM411	$9000 USD	$100 USD	Estimate 5–10 years	Rear or front of vehicle	The sensor provides friction reading, which is readily convertible to Brine Fraction (i.e. salt concentration)

Q6. How do you use the information provided by the salinity sensor(s)?

Thirteen responses were obtained for this question, with all comments shown in Table 9.

Table 9. Survey answers about the usage of information provided by the salinity sensor(s)

Agency	Comments
Minnesota DOT	Freeze point determination
New York DOT	Field staff may use to view pavement condition such as presence of ice.
Teconer Ltd.	Information is used to assess: - whether there is risk for refreezing during lowering surface temperatures or light precipitation/condensation - quality of taken gritting action (Is there enough salt or anti-icer?)
North Dakota DOT	Used to determine the current freezing temperature of the roadway.
Ohio DOT	The information is used to determine whether or not the roadway is chemically wet.
Utah DOT	We use them to see if our application rate is adequate and have been able to cut down on our application rates based on salinity on pavement at next application.
Utah DOT	These sensors are used primarily by road maintenance crews to adjust or re-apply mitigation materials.
Kansas DOT	We currently report a chemical factor
Wisconsin DOT	To determine future chemical applications
Massachusetts DOT	They are just part of our RWIS info. We don't have as much confidence in them as they are in the last years of their life.
AIBAN Vinterservice	Typical Sobo20 are used before workers go home. Sometimes the result is that there is enough salt on the road. Another way we use Sobo 20 is to measure where the salt spreader, place the salt on the road. In that way we measure on a wet road 2 hours after spreading salt.
Brun-Way Highways Operations	We have 5 RWIS with fixed salinity sensor (puck) incased in the pavement. It is used to forecast road surface conditions
University of Waterloo	Research purpose, to model residual salts.

Q7. Please explain when and how often the salinity sensors are used.

A total of 12 responses were obtained for this question. Details are provided in Table 10.

Table 10. Survey answers about when and how often the salinity sensors are used

Agency	Comments
Minnesota DOT	The pucks are at each RWIS station.
New York DOT	Limited data is only rarely viewed by field staff via contractor hosted website.
Teconer Ltd.	For refreezing studies the system is still in experimental use. For quality control the use is expanding, but still not in daily use in all areas.
North Dakota DOT	Our Staff uses the readings most of the winter, MDSS also utilizes the information.
Ohio DOT	They are part of our RWIS network and used by our Weather and Pavement Forecasting vendor.
Utah DOT	I used them after each storm and during to check for prop application rate.
Utah DOT	These sensors are used during winter storm events.
Kansas DOT	The salinity sensors are in service year route. The chemical factor tells you the amount a residual salt on the road surface.
Wisconsin DOT	Occasionally.
Massachusetts DOT	They are included in our RWIS data.
AIBAN Vinterservice	After salting the SOBO 20 is used every day (until there is not more salt).
Brun-Way Highways Operations	Fixed in the pavement, use for road condition forecasted.

Q8. What is the accuracy of the salinity sensor(s) you use? (Please list each salinity sensor you use and rate the accuracy of the measurement as (a) 100% accurate, (b) 90 to 75% accurate, (c) less than 75% accurate. Provide additional comments as you see fit.).

Ten agencies provided responses to this question. The major share of the obtained answers included low accuracy (e.g., less than 75% accurate) and lack of a salinity test. Detailed responses are provided in Table 11.

Table 11. Comments on the accuracy of salinity sensors adopted by the survey respondents

Agency	Comments
Minnesota DOT	c. The passive sensors are very poor at determining salinity
New York DOT	We have never conducted tests to determine this.
Teconer Ltd	The measurement result (friction) is providing Brine Fraction, i.e. concentration at a given temperature. The accuracy of concentration is about 3 % for NaCl (about 0.15 in Brine Fraction).
North Dakota DOT	We have not tested this.
Ohio DOT	I am not sure of their accuracy.
Utah DOT	We perform testing in the field twice a year. We do not record measurements but detect if the sensor is working or not. I would estimate (b), 90 to 75%. The sensor we use is the Lufft IRS21.
Wisconsin DOT	c
Massachusetts DOT	Less than 75% accurate, because of age.
AIBAN Vinterservice	When they are more than 1.5 gram salt per square meter, Sobo 20 is 100% accurate (more than 90% accurate). Measurements placed on 2 roads with 12 km between, but on the same salting route have a very high correlation.
University of Waterloo	We used two years, so far I remember it prediction level is questionable

Q9. If you use salinity sensors mounted on vehicles, what type of vehicle are they mounted on?

There were 12 responses to this question. However, 9 (75%) of them responded with “We do not use vehicle-mounted salinity sensors”; only one respondent, from Teconer, Ltd., explained that Teconer mounts salinity sensors on the “Snowplow,” “Patrol,” and “Spreader” winter maintenance vehicles. Detailed information and additional comments are provided in Table 12.

Table 12. The type of vehicles that survey respondents mounted their salinity sensors on

Agency	Snowplow	Patrol vehicle	Spreader	We do not use vehicle-mounted salinity sensors	Other (please explain)
Minnesota DOT				√	
New York DOT				√	
Teconer Ltd	√	√	√		
North Dakota DOT				√	
Ohio DOT				√	
Utah DOT					Jeff in our RWS group at 801-887-3703 can get you all the info on sensors we have used, brands etc.
Utah DOT				√	
Kansas DOT				√	
Wisconsin DOT				√	
Massachusetts DOT				√	We are looking as several to demo but have not purchased any yet.
AIBAN Vinterservice				√	
Brun-Way Highways Operations					I was not aware of these mobile salinity sensors. I would be interested to learn more on it.

Q10. Would you be willing to share your experience using salinity sensors?

There were 12 responses to this question; 11 answered “Yes” and 1 answered “No.”

Q11. If a mobile vehicle-mounted salinity sensor was available, would you consider using this technology to support your winter maintenance operations?

In total, 30 respondents answered this question, of which 7 respondents answered “Yes,” 17 responded “I would consider it,” 3 answered “Not sure,” and 3 answered “No” (Figure 15). Additional comments are provided in Table 13.

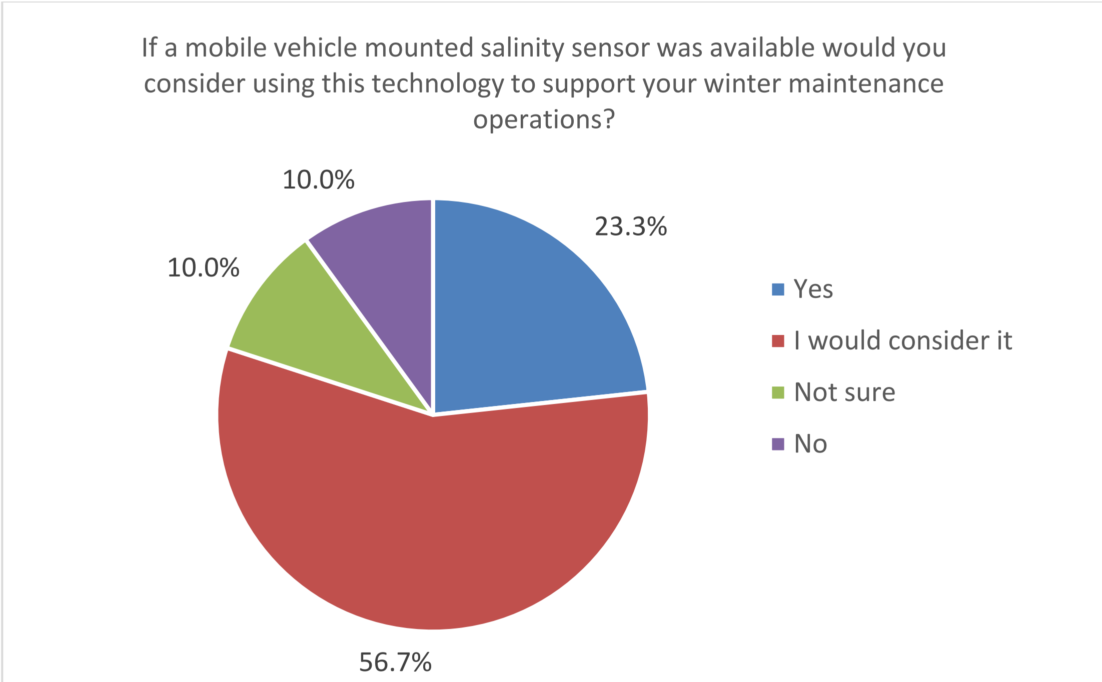


Figure 15. Survey results showing if respondents would consider using an available mobile vehicle-mounted salinity sensor

Table 13. Additional comments on the considerations of using mobile vehicle-mounted salinity sensor

Agency	Comments
The Narwhal Group	As a weather forecasting operation, it could be utilized by us or our clients.
University of Birmingham	Would be interested to see it and to link with current research initiatives,
Lufft USA Inc.	Lufft does manufacture a mobile RWIS sensor.
Ohio DOT	Possibly if the price was low enough and it also provided air and pavement temperature readings.
Wisconsin DOT	I would have to be sold on the accuracy.
Massachusetts DOT	The cost currently is the biggest drawback.
Minnesota DOT	Needs to be accurate and dependable.
AIBAN Vinterservice	Yes, if measurements correlation are good enough.
Brun-Way Highways Operations	Depending on the price of these sensors

Q12. What do you see as barriers to using a mobile salinity sensor in your winter maintenance operations?

A total of 27 responses were collected for this question. According to the answers to some of above questions, e.g., Q8, it is not surprising to see that "accuracy" was reported by about 11 respondents as one of barriers to mobile salinity sensor usage. Comparatively, "cost" is another major concern reported by about 10 respondents, followed by sensor durability, effectiveness, and convenience, etc. Detailed comments are provided in Table 14.

Table 14. Comments on barriers to mobile salinity sensor usage in winter maintenance operations

Agency	Comments
Iowa DOT	Accuracy. We have tried using them in the past but eventually accuracy undermined the value of the sensor.
The Narwhal Group	Cost, I assume is the main barrier.
Minnesota DOT	Ease of mounting and durability.
Nevada DOT	Cost, implementation and management.
North Dakota DOT	We don't have any interest in them at this time
New York DOT	Costs to acquire, operate & maintain. Difficulty getting field staff buy in.
University of Birmingham	Depends on the technology. Consistency in a harsh environment would be an obvious concern.
Teconer Ltd	(Sorry, we are making the sensor, not directly in operations.)
Pennsylvania DOT	May not be effective in heavier snow events where snow is laying on top of liquid on the road.
North Dakota DOT	Accuracy.
Ohio DOT	Cost, accuracy, subsurface temperature, durability.
	Accuracy, durability, culture.
	Because of the miles of road the cost to equip enough vehicles would high. The mobility and reliability of the equipment mounted on the vehicle needs to be proved.
Pennsylvania DOT	Cost- we have a fleet of 2700 trucks and 90,000 miles to maintain
Alberta Ministry of Transportation	In Alberta, all highway maintenance is done by contractors. Our department would need to do a contract change for short-term introduction of salinity sensors, or take longer to introduce them as part of new contract award.
Utah DOT	Accuracy of sensor.
Sustainable Salting Solutions, LLC	Multitude of chemicals on the pavement that could affect salinity readings. Also sensors seem to have high failure rates in the real environments.
Utah DOT	Just ensuring that the positioning on the vehicle is optimal for precise measurements. I am not involved directly in maintenance operations.
Kansas DOT	Cost/Need/Sustainability.
Wisconsin DOT	Accuracy in that environment.
Massachusetts DOT	Cost.
Iowa DOT	Not sure.
Minnesota DOT	Accuracy and dependability.
AIBAN Vinterservice	The accuracy.
Brun-Way Highways Operations	Price and maintenance of the sensors.

Agency	Comments
University of Waterloo	If we need to use manually, it will not work. It should be like weather forecasting, why not we imagine residual salt data will also be forecasted by RWIS/like service.
	Funding.

Q13. What do you see as potential benefits of using mobile salinity sensors in your winter maintenance operations?

A total of 25 agencies responded this question. Responses generally involved the potential benefits of salinity sensors in controlling salt application and their positive assistance in winter maintenance practice (around 90%), which reflects a willingness to consider using this technology in the future. Detailed comments are shown in Table 15.

Table 15. Comments on the potential benefits of using mobile salinity sensors in winter maintenance operations

Agency	Comments
Iowa DOT	Many. Mostly being able to assess whether the current treatment is holding out, and where it needs to be retreated (and by how much).
The Narwhal Group	Improve pavement condition forecasts for our clients.
Minnesota DOT	Great info to have if accurate.
Nevada DOT	Identify vulnerable areas and environmental sensitive areas and potential structural damaging level.
North Dakota DOT	NA.
New York DOT	If affordable these could provide another tool for chemical application decision making.
University of Birmingham	Controlling spread rates dynamically based on existing measurements.
Lufft USA Inc.	Timely data.
Teconer Ltd.	The benefits are: - Less liquid spray (better visibility when following another vehicle). Makes it possible to adjust salt or anti-icer amount so that partial freezing (ice fraction / brine fraction) is properly controlled - Potential for saving salt and anti-icers - Allows location- and measurement-based control of gritting
Pennsylvania DOT	Possible reduction in material use.
North Dakota DOT	Added information to input into MDSS.
Ohio DOT	If they also provide pavement and air temperature data, they would serve multiple purposes.
	Reduced application of chlorides and therefore cost savings.
	Limit salt consignation.
Pennsylvania DOT	Extra piece of data to make decisions from.

Agency	Comments
Alberta Ministry of Transportation	Our beats tend to be long, and cycle time can be several hours. Knowing if there were residual chlorides on highways would allow us to adjust application rates when we do get back to a location that is far away from the shop.
Utah DOT	Could check any area vs stationary sensor in pavement.
Sustainable Salting Solutions, LLC	Wow....timing chemical applications...more precision.
Utah DOT	I am not involved directly in maintenance operations.
Wisconsin DOT	One could get reading for an area and not just a point.
Massachusetts DOT	If you can have an accurate reading of the sodium chloride on the pavement allows the agency to apply when needed not at the appearance of needing it. Good tool when becomes more cost effective.
Iowa DOT	Tracking salt usage.
Minnesota DOT	Better information, better decisions.
Brun-Way Highways Operations	These sensors could be another tool for the road patrollers to make the proper decisions. It would have a huge benefit for road safety and for reducing material quantity.
University of Waterloo	Reduce salt amount, save direct and indirect costs for all stakeholders and taxpayers.

Q14. Do you have contacts or documents relevant to vehicle-mounted salinity sensors you would recommend to the researchers of this project? (Please provide links to the documents below or upload here.)

There were 22 responses to this question, 6 of which provided direct or indirect additional contact information relevant to vehicle-mounted salinity sensors. Detailed comments are listed in Table 16.

Table 16. Comments on providing additional contacts or documents relevant to vehicle-mounted salinity sensors

Agency	Comments
University of Birmingham	You have seen our paper already.
Lufft USA Inc.	Please see the email to Laura Fay. http://lufft-marwis.com/en_US/specifications.
Teconer Ltd	Please, contact Jim Boyle, The KRS Sales Group, 3 Fayfarer Drive, Plymouth, MA 02360, USA, phone: (224) 600-3379, Email: jboyle@thekrssalesgroup.com.
Sustainable Salting Solutions, LLC	Ohio University did some work a number of years ago with Ohio DOT support. It was a good study, but they had problems with the SOBO 20 salinity meter as I recall. I have the study somewhere in my files.
Kansas DOT	Lufft, MARWIS, Contact Mike Corbett, 919-623-8952, mike.corbett@transequipserv.com
Massachusetts DOT	There is a company in Massachusetts selling to airports.

APPENDIX B. IN-PAVEMENT AND PORTABLE SALINITY SENSING TECHNOLOGY

In-Pavement Salinity Sensors

In-pavement sensors are commonly used to measure the salinity of the road surface. In-pavement sensors determine the salt concentration of the road surface by testing the electrical conductivity of the environment. However, as indicated by the name, in-pavement sensors only provide information at a fixed location (Figure 16). These sensors have been used as reference points for verifying the presence of salt rather than as a tool that provides details about salt concentration and variations in salt concentration on the roadway. Some in-pavement sensors can also test the temperature or humidity of pavement surfaces (Sherif and Hassan 2004).

Cai et al. 2014

Figure 16. Embedded pavement sensor

Currently, several companies can provide in-pavement sensors with stable testing capability. Vaisala and Boschung supply in-pavement sensors to monitor the surface condition of bridges and pavements. Vaisala sensors mainly include bridge surface, road and runway surface, depth (DRS511), and SSI passive pavement sensors (http://www.vaisala.com/en/products/Pages/default.aspx). The Boschung sensors include the BOSO III, Arctis, IT-Sens, and Bopas (http://www.boschung.com/en/).

Vaisala Bridge Surface Sensor

The Vaisala bridge surface sensor can measure the pavement surface temperature and ground temperature at about 60 mm in depth. It can also detect freezing point depression, chemical amount, black ice, and the surface condition of the pavement, including water/ice layer thickness and presence of snow and moisture. In addition, it can provide an alert when rain, frost, or ice are detected. The sensor is thermally passive, which means it does not disturb the surface. The maker states that the robust epoxy body of the sensor guarantees its testing accuracy, even allowing for as much as 10 mm in wear, and it can be installed in the wheel track.

Vaisala In-Pavement Runway Sensor DRS511

DRS511 is similar to the bridge surface sensor, can measure pavement surface temperature and ground temperature at a depth of about 300 mm, and can detect freezing point depression, chemical amount, black ice, and the surface condition of the pavement, including water/ice layer thickness and the presence of snow and moisture. The maker states that with the developed epoxy material, the testing accuracy can be guaranteed even with as much as 35 mm of wear.

Vaisala SSI Passive Pavement Sensor FP2000

FP2000 can detect pavement condition and determine whether water or a chemical solution exists on the pavement. It is a durable and reliable sensor that can withstand heavy traffic, tire chains, snowplows, and extreme weather conditions. The maker states that the FP2000 utilizes patented technology consisting of a combination of temperature and capacitance sensors and two sets of four-point sensing nodes to measure pavement condition, as well as a sensor that collects moisture and chemical information.

Boschung IT-Sens Sensor

Boschung IT-Sens sensor is an in-pavement sensor that can monitor pavement surface condition. It has three versions: Traffic Control Support (TCS), Winter Service Support-Basic (WSS-B), and Winter Service Support-Evolution (WSS-E). The specifications of these three versions are listed in Table 17.

Table 17. Specifications of the Boschung IT-Sens sensors

Specifications	TCS	WSS-Basic	WSS-Evolution
Survival range	-40ºC to +80ºC	-40ºC to +80ºC	-40ºC to +80ºC
Pavement Surface Temp	-40ºC to +75 ºC	-40ºC to +80ºC	-40ºC to +80ºC
Accuracy	-15ºC to +10ºC: ± 0.2ºC else: ± 0.8ºC	-15ºC to +10ºC: ± 0.2ºC else: ± 0.8ºC	-15ºC to +10ºC: ± 0.2ºC else: ± 0.8ºC
Resolution	0.1ºC	0.1ºC	0.1ºC
Water Film Thickness	0 mm to 10 mm	0 mm to 10 mm	0 mm to 10 mm
Resolution	0.01 mm	0.01 mm	0.01 mm
Pavement Status	Dry/moist/wet/ flowing/ice	Dry/moist/wet/flowing/ice/ snow/frost	Dry/moist/wet/ flowing/ice/snow/frost
Freeze-Point Temp	N/A	-30ºC to 0ºC	-30ºC to 0ºC
Accuracy	N/A	-2.5ºC to 0ºC: ± 0.5ºC else: ± 20%	-5.0ºC to 0ºC: ± 0.5ºC else: ± 15%
Resolution	N/A	0.1ºC	0.1ºC
Chemical Factor	N/A	0% to 100%	0% to 100%
Cable Length Standard	30 m	30 m	30 m
Cable Length Extension	Up to 600 m (with kit)	Up to 600 m (with kit)	Up to 600 m (with kit)
Communication	R5-485 (CAN BUS optional)	R5-485 (CAN BUS optional)	R5-485 (CAN BUS optional)
Operating Voltage	12 to 24 V DC	12 to 24 V DC	12 to 24 V DC
Power Consumption	< 0.5 W	0.5 W	0.5 W
Diameter	90 mm	90 mm	90 mm
Height	42 mm	42 mm	42 mm
Weight (with 30m cable)	3.250 Kg	3.250 Kg	3.250 Kg
Enclosure Rating	IP 68	IP 68	IP 68
Chemical Resistance	Excellent	Excellent	Excellent
MTBF*	> 60,000 hours	> 60,000 hours	> 60,000 hours

* MTBF = mean time between failures

Boschung Bopas Sensor

Boschung Bopas sensor used in combination with RWIS measures the condition of the pavement and provides information on pavement temperature, pavement conditions (dry, humid, wet, black ice, frost), and presence of salt (salt concentration and remaining quantity of salt). It features three alarm levels for present time and forecasts and is able to distinguish between black ice, ice, and frozen snow.

Boschung BOSO III System

The BOSO III system uses an active/passive sensor design. The passive element measures pavement temperature, road condition (wet/dry), and water film thickness. The active element cools itself by 3.6ºF below the road surface temperature to determine the freezing point of the liquid present (calculated) and alerts the user, via the BORRMA software, to a possible icy condition. This sensor is capable of spraying a Boschung FAST or micro-FAST system. It also has features similar to those of the Bopas sensor, in that it has three alarm levels for present time and forecasts with a measured ice warning feature included in the second alarm level.

Boschung ARCTIS

Boschung ARCTIS, similarly to the BOSO III sensor, cools itself (by up to 27ºF) below the road surface temperature and displays the actual freezing point via the BORRMA software (calculated), regardless of the chemical on the roadway, eliminating the need for chemical algorithms and look-up tables. It also is capable of reporting pavement temperature, pavement status (dry, humid, etc.), water layer thickness, freezing point temperature (calculated), salt factor/chemical concentration, and the remaining quantity of salt.

Lufft ARS31Pro-UMB

The in-pavement sensor Lufft ARS31Pro-UMB is used to determine the freezing temperature of a mixture-independent liquid on the pavement surface. It can be used to measure (1) salt concentration (e.g., NaCl, $CaCl_2$, and $MgCl_2$), (2) product concentration (e.g., potassium acetate and potassium formate), and (3) freezing temperature (independent of mixture). Moreover, the ARS31Pro-UMB is able to measure dry/wet conditions and road surface temperature. Its replaceable working feature means that it can be built into new and existing UMB networks. The technical data for the Lufft ARS31Pro-UMB and information about its external road surface temperature and freezing point measurements are shown in Table 18.

Table 18. Key features of Lufft ARS31Pro-UMB

Technical Data	Dimensions	∅ 120 mm, height 50 mm
	Weight	Approx. 1100 g
	Detectable road conditions	Dry/wet/critical wetness/ice alert
	Storage temperature	-40ºC to 70ºC (-40ºF to 158ºF)
	Protection type	IP 68
	Op. power consumption	9 to 36 V DC
	Plug	CAGE CLAMP, WAGO (cross-section $<$ 0.5 mm^2)
	Op. temperature range	-40ºC to 70ºC (-40ºF to 158ºF)
	Operating humidity range	0% to 100% RH
	Power consumption	Approx. 30 W
	Interface	RS485, baud rate: 2,400 to 38,400 blt/s (default: 19,200)
External Road Surface Temp	Principle	NTC
	Measuring range	-40ºC to 70ºC (-40ºF to 158ºF)
	Accuracy	± 0.2ºC (-10ºC to 10ºC), or ± 0.5ºC
	Resolution	0.1
Freezing Point	Measuring range	-20ºC to 0ºC (-4ºF to 32ºF)
	Accuracy	± 0.5ºC RMS for Tg $>$ -15ºC, or ± 1.5ºC RMS for Tg $<$ -15ºC (at NaCl)
Accessories	UMB interface converter ISOCON-UMB	
	Spare part cap + electronics ARS31 Pro-UMB	
	Surge protector	
	Digital-analog-converter DACON8-UMB	

MH Corbin VX21/VX22

The VX pavement sensors are sealed and potted devices that measure road surface and subgrade temperatures, as well as conductivity (reporting the presence of salt) and the presence of moisture on the roadway. The VX sensors are wireless and can communicate up to 600 ft. The sensors can be added to a RWIS or used as a standalone sensor. The standalone system comes with a VXMS radio module, cellular modem, and sealed battery. Information is transmitted and viewed using the web-based GUI, and web-based software can be viewed from any device connected to the internet. The sensors can be installed in 30 minutes on roadways and bridge decks. The sensor has a battery life of five to seven years. A summary of the working parameters and functional capabilities of the sensors are shown in Figure 17.

Pavement Sensor Options:

VX21-1 Single Road Surface Temperature Probe

VX21-2 Road Surface and Sub-Grade Temperature Probes

			VX21-1	VX21-2
Techincal Data	Dimensions	4.00" DIA x 2.875" H	✓	✓
	Road Conditions Measured	Wet/Dry/Chemical	✓	✓
	Interface	915MHz RF	✓	✓
	Storage Temperature Range	-40° to 80° C	✓	✓
	Power Source	3.7VDC 38Ahr Battery	✓	✓
	Communications	915 MHz RF	✓	✓
	Operating Temperature Range	-40° to 80° C	✓	✓
	Operating Humidity Range	0....100% RH	✓	✓
Road Surface Temperature	Principle	Digital/Microcontroller	✓	✓
	Measuring Range	-55° - 125° C	✓	✓
	Accuracy	±0.5° C	✓	✓
	Resolution	12 Bit	✓	✓
Sub-Surface Temperature	Principle	Digital/Microcontroller		✓
	Measuring Range	-55° - 125° C		✓
	Accuracy	±0.5° C		✓
	Resolution	12 Bit		✓

MH Corbin n.d.

Figure 17. Summary of VX21-1/VX21-2 pavement sensor options

Table 19 provides a summary of in-pavement salinity sensors, with example photographs, manufacturers, model names, and references for additional information.

Table 19. Summary of in-pavement salinity sensors

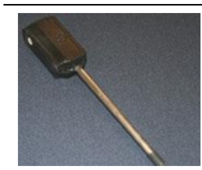
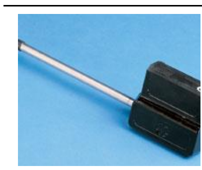
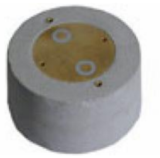
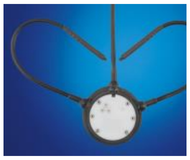
Photo	Company	Model	Reference
	Vaisala	Bridge surface sensor	http://www.vaisala.com/en/products/surfacesensors/Pages/Bridge-Surface-Sensor.aspx
	Vaisala	DRS511	http://www.vaisala.com/en/products/surfacesensors/Pages/DRS511.aspx

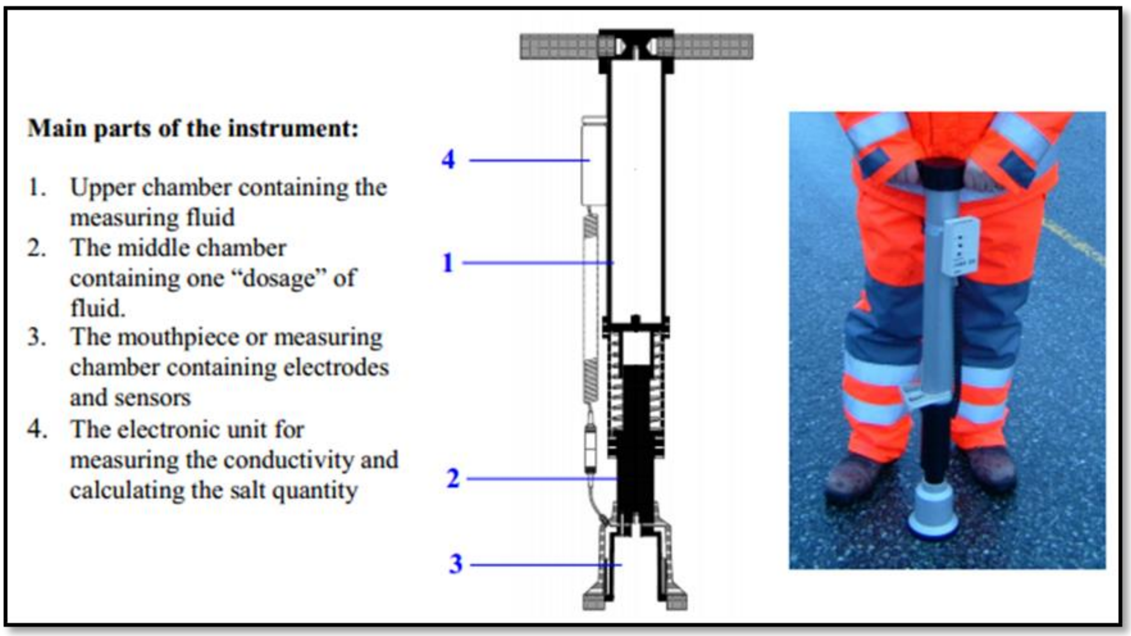
Photo	Company	Model	Reference
	Vaisala	SSI FP2000	http://www.vaisala.com/en/roads/products/roadweathersensors/Pages/FP2000.aspx
	Boschung	IT-Sens	http://www.boschungamerica.com/pavement-sensors
	Boschung	Bopas	http://www.boschungamerica.com/pavement-sensors
	Boschung	BOSO III	http://www.boschungamerica.com/pavement-sensors
	Boschung	ARCTIS	http://www.boschungamerica.com/pavement-sensors
	Lufft	ARS31Pro-UMB	http://www.lufft.com/en/products/road-sensors/intelligent-active-road-sensor-ars31pro-umb-8810u051/
	Lufft	IRS31Pro-UMB	http://www.lufft.com/en/products/road-sensors/intelligent-passive-road-sensor-irs31pro-umb-8910u102/
	MH Corbin	VX21/VX22	http://www.mhcorbin.com/products/manufactured-products/vx-pavement-sensor

Portable (But Not Vehicle-Mounted) Sensors

There are many types of portable salinity sensors that test the concentration of salt solutions. However, most are only capable of testing the liquid solutions in a container rather than the salt concentration on pavement surfaces (Hussain and Hawas 2008, Rahman 2011) and are therefore limited to measuring residual chloride on the pavement. Portable sensors provide flexibility in measurement due to their easy and fast operation, but these sensors require manual measurement, which may decrease efficiency, create operation inconvenience, and cause potential safety issues if personnel have to leave the vehicle and walk onto the road to collect data. Available portable salinity sensors are presented below.

Boschung SOBO-20

SOBO-20 is a salt measuring product manufactured by Boschung that is used by winter maintenance personnel to quantify the residual salt content on a pavement surface. According to the technical data provided by the manufacturer, the SOBO-20 is 900 mm tall and 60 mm in diameter, with a container capacity of about 1.5 L that allows for about 35 measurements. Figure 18 shows the physical design of the SOBO-20, including its four main parts.



From Lysbakken and Lalagüe 2013, which cites figure is from Nygaard 2003, which is actually Nygaard 2005

Figure 18. Schematic drawing and photograph of the SOBO-20 salinity measuring device

Similar to the working principles of many conventional salinity measurement instruments, the SOBO-20 operates by measuring the electrical conductivity of a mixture by adding a certain amount of fluid (e.g., 85% water and 15% acetone) to the road surface and calculating the residual salt content based on the relationship between electrical conductivity and salt concentration. The measurement can be done in a few seconds and is reported in g/m^2. However, based on experience in the United Kingdom, it shows limited practical use as a suitable mobile pavement analysis device because it involves injection of anti-freezing liquid into a small chamber pressed onto the pavement (Highways Agency 2007). Table 20 summarizes the beneficial features and limitations of the SOBO-20.

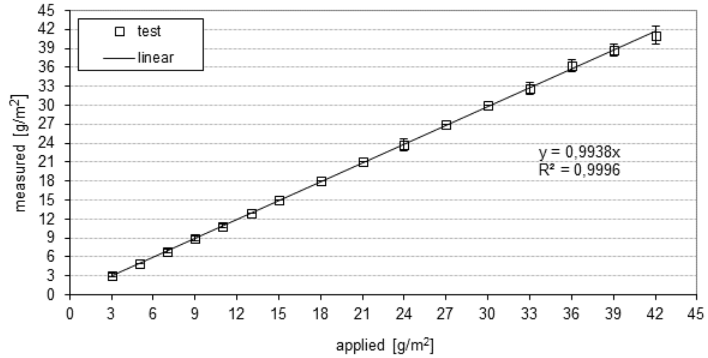
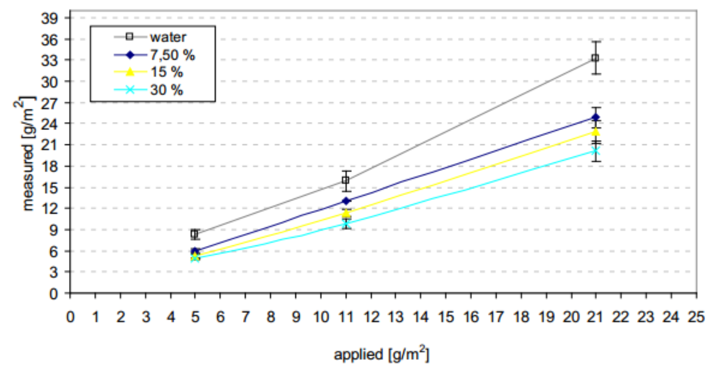
Table 20. Beneficial features and limitations of the SOBO-20

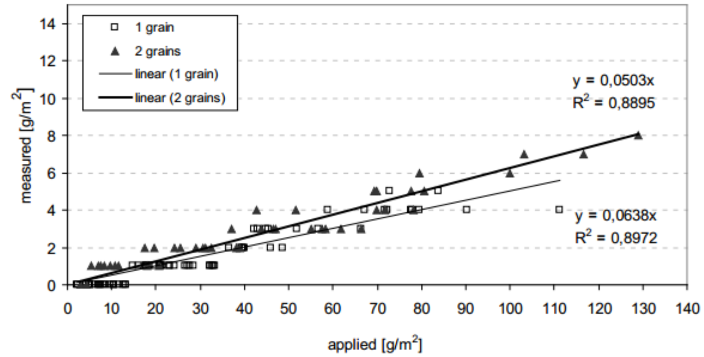
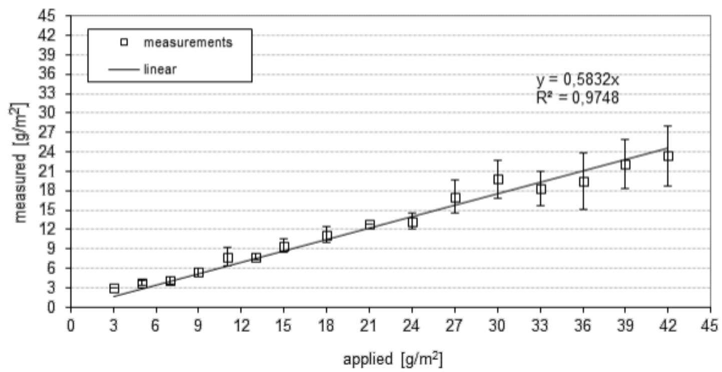
Beneficial features	Limitations
1. Measures salt in terms of quantity per unit area (g/m^2). 2. Works when minimal fluid is available on the pavement surface because of the addition of the water and acetone mixture. 3. Can be used on dry road surface. 4. Portable and requires no installation or power supply. 5. Measuring procedure is simple. 6. Produces instantaneous readings and no further analysis is required.	1. Only detects between 5% and 6% of dry salt particles. 2. Does not allow salt crystals to dissolve. 3. When measuring dry or pre-wetted salt, the displayed value has to be interpreted only as the quantity of dissolved salt on the road surface, not total salt quantity.

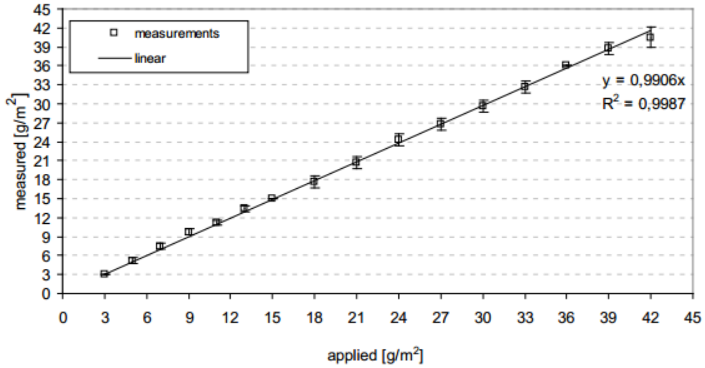
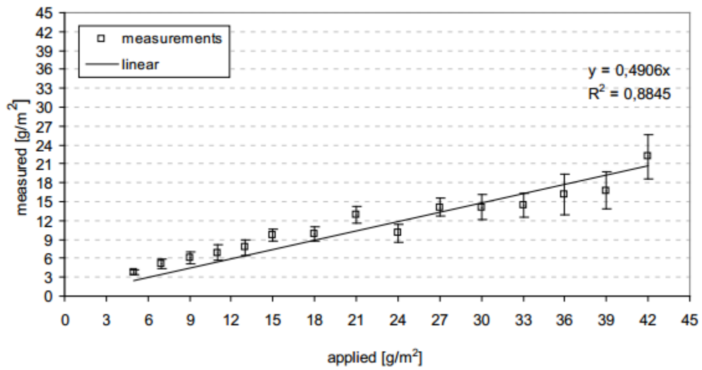
Lysbakken and Lalagüe 2013

Table 21 provides information based on a series of laboratory and field tests conducted by Lysbakken and Lalagüe (2013) that highlights the performance and features of the SOBO-20 in practical applications.

Table 21. Performance and features of SOBO-20 in application

Test	Surface texture	Experimental figure	Conclusion
Calibration test	Smooth		According to the good fitness of applied and detected salt quantities (R = 0.9996), it shows that SOBO-20 has quite accurate performance in measuring dissolved salt on smooth road surfaces.
Test of the acetone content of the measuring fluid	Smooth		Testing the effect of acetone content in the measuring fluid on the measurements indicates that lowering the acetone content will increase errors in the readings. If only distilled water is used in the SOBO-20 measurements, a range of 45% to 66% errors will occur greater than the actual applied quantity.

Test	Surface texture	Experimental figure	Conclusion
Measurements of salt grains	Smooth		When measuring salt grains, SOBO-20 is only able to detect approximately 5% to 6% of the salt quantity for the one salt grain or two salt grain measurements.
Measurements of re-crystallized salt	Smooth		Based on the test results and regression curve when re-crystallized brine is measured, SOBO-20 underestimates detection, with only about 58% of the applied salt observed.

Test	Surface texture	Experimental figure	Conclusion
Calibration test	Asphalt		Similar to the good performance on the smooth surface, SOBO-20 is able to quite accurately perform measurements on asphalt pavement with a regression R^2 close to 1.
Measurements of re-crystallized salt	Asphalt		Compared to the underestimated measurements produced by SOBO-20 on smooth surfaces (approximate 58%), when measuring re-crystallized salt on asphalt pavements, SOBO-20 on average shows a lower percent of detection, with only about 49% of the quantity able to be read.

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The advantages and disadvantages of in-pavement salinity sensors and portable (but not vehicle-mounted) salinity sensors are summarized in Table 22.

Table 22. Summary of the advantages and disadvantages of in-pavement and portable (but not vehicle-mounted) salinity sensors

Salinity sensor type	Advantages	Disadvantages
In-pavement salinity sensors	• Easy installation • Can be networked • Comparatively inexpensive	• Only provide information at their location • May need to be replaced more frequently due to harsh conditions and with re-paving.
Portable (but not vehicle-mounted) salinity sensors	• Flexible measurement locations • Easy maintenance • Comparatively moderate cost	• Only provides data at location of testing. • Require manual measurements and therefore the need to leave the vehicle, which increases time and inconvenience. • Safety issues caused by leaving the vehicle to take measurements in the roadway.