ROAD STATUS SENSORS
A COMPARISON OF ACTIVE AND PASSIVE SENSORS

Author: Patrik Jonsson

Department of Information Technology and Media, Mid Sweden University, SE-831 25 Östersund
Saab Security Box 360, SE-831 25 Östersund.
email: patrik.jonsson@saabgroup.com
phone: +46 70 655 63 18

KEYWORDS

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ABSTRACT

Knowledge of the road status and specifically knowledge of the freezing point of the road surface fluid is crucial in order to perform effective and environmentally safe road maintenance. Road status sensors installed in the road can be passive conductivity sensors or active freezing point sensors. In this paper the output from a passive and an active sensor has been studied when the sensors has been contaminated with common chemicals that can be present on the road surface such as oil, alcohol and glycol. The results indicated that only intelligent active sensors reliably can detect freezing points on the road surface.

INTRODUCTION

In regions with sub-zero temperatures traffic safety can be significantly improved by correct road maintenance. Water freezes to snow and ice causing a drastic decrease of the friction of the road. A decrease of road friction increases the risk of traffic accidents and it causes economic losses due to delays in the transport sectors. In order to eliminate the impact of weather, extensive road maintenance is performed in the sub-zero regions. Road maintenance involves snow removal and the spread of anti-icing chemicals [1].

When electronics and sensors made their entrance in road maintenance in the beginning of the 1980's, the manual road condition supervision was about to become superfluous. A road status supervision system called RWiS (Road Weather information System) was introduced in several countries. Initially the countries included Sweden, Finland and the UK [1]. To start with, only standard meteorological weather parameters were observed, such as air temperature, air humidity, wind speed and wind direction. Sensors that gave information about road condition were limited to in situ road surface temperature sensors [1]. These sensors together with national weather forecasts made it possible to determine possible frost buildup on the road surface [2]. Indications of possible road frost buildup initiated anti-icing

procedures, usually the spreading of sodium chloride (NaCl), which is the cheapest anti-icing agent, or Calcium Chloride (CaCl$_2$) [3]. One problem was that the knowledge of freezing point change due to the spreading of deicing fluids or salts was not exactly known, it was only estimated from the amount of anti-icing or de-icing material spread on the road surface. The problem with not knowing the actual freezing point is that it may lead to spreading too much or too little anti-icing chemicals. Too little anti-icing chemicals being spread can cause severe traffic accidents due to slippery roads, and too much may give a negative impact on the environment in terms of contaminated ground water and wells [3, 4].

Objective

The aim with this paper is to show the reliability of the freezing point data retrieved from common road condition sensors. The focus is towards freezing point detection sensors installed in the road surface. There are two main types of surface mounted road condition sensors; passive and active sensors. Passive surface mounted sensors normally detect the conductivity of the road surface fluid and the freezing point is estimated from the conductivity value. An active surface mounted sensor tries to detect the actual freezing point by cooling the road surface fluid until it freezes and then detect the freezing point.

Delimitation

In the last few years some none intrusive sensors has been introduced on the market. Non intrusive sensors can be non intrusive passive camera image systems with image recognition algorithms [5, 6] or active non intrusive sensors based on illumination of the road surface with IR lasers or LED's together with IR detectors [7]. The non intrusive sensors are not discussed in this paper since they are more or less at a development stage and they are currently only used by national road administrations for evaluation [7]. As freezing point depression fluid only sodium chloride (NaCl) has been used in the experiments.

BACKGROUND AND THEORY

Chemicals used for freezing point depression on roads

Chemicals, or 'road salts', used for road maintenance that lowers the freezing point is sodium chloride (NaCl), calcium chloride (CaCl$_2$), magnesium chloride (MgCl$_2$) and calcium magnesium acetate (CMA). Other chemicals that are used are potassium acetate, urea and ethylene glycol. When road maintenance is done, normally sodium chloride (NaCl) and calcium choride (CaCl$_2$) is used because of the pricing for especially sodium chloride is lower than for other deicing substances [3]. In the last years the environmental effects of road salting has raised the need for alternative deicing fluids such as different sugar mixtures [1].

Properties of water and dilute chloride mixtures

Water undergoes a phase shift from liquid to solid state during freezing as in Figure 1. Water extracts during the formation of ice and according to the second law of thermodynamics, the water will release its latent heat of fusion when it undergoes a change from water to a more ordered form as ice crystals.
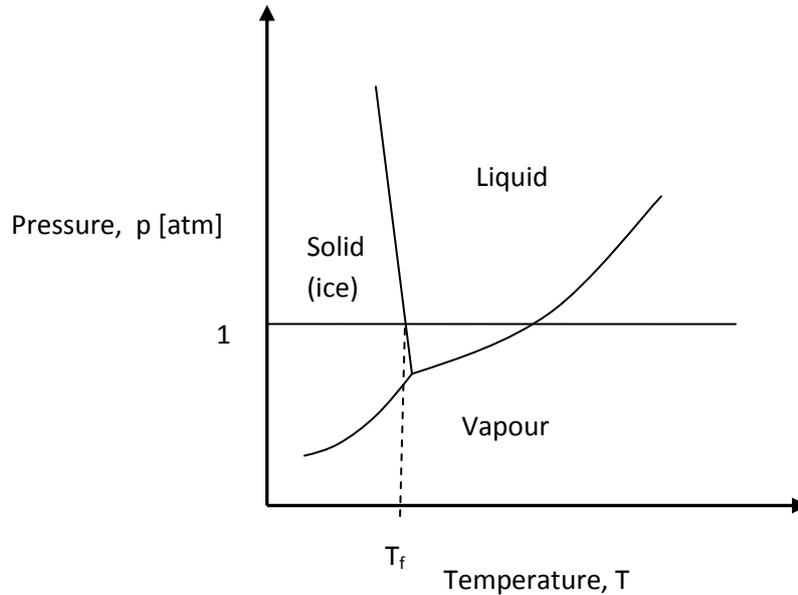
Figure 1. Phase diagram for water (from [8]). T_f is the freezing point.

When water is cooled to its freezing point at 0° C, it may not freeze. In fact, distilled water that has a freezing point of 0° C can be cooled down to -40° C without being transformed to solid ice state. When the fluid is cooled below its freezing point it is called supercooled. Any contamination of the distilled water will make the transition from liquid to solid at a temperature higher than -40° C. The phenomenon of supercooling is well known and applies to many fluids if the cooling is done sufficiently rapid [9].

When cooling the liquid water solution it can be seen from the isobar in Figure 2 that the water and salt solution will have a clear knee when the first order exothermic transition, or freezing, occurs [8]. Figure 2 shows the phenomenon of supercooling that occurs before time t_f, and the freezing point T_f can be observed as the knee after the freezing has occurred.
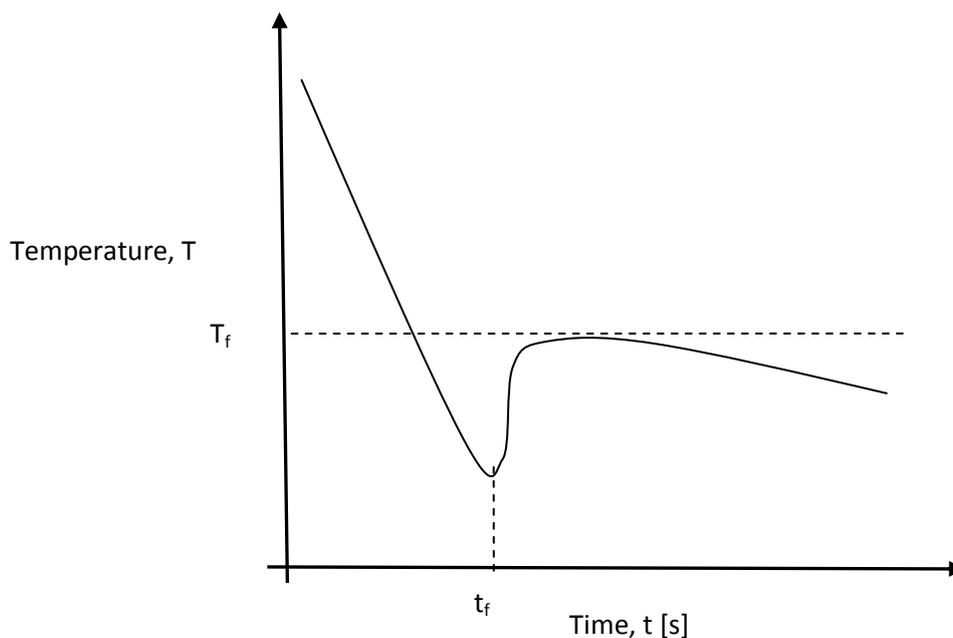
Figure 2. Typical freezing point curve for water. T_f is the freezing point that occurs at time t_f. Picture principle reproduced from [9].

The phenomenon of supercooling and the thermodynamic laws that state the release of latent heat of fusion are useful when observing the phase shift from water to solid. As seen from the freezing curve above, water is cooled below its freezing point. After a short time the supercooled water will form ice crystals and the water will release its latent heat of fusion. This release of heat can be observed as a raise of temperature of the supercooled water [8]. By finding the maxima of temperature after the formation of ice crystals have started, the freezing point can be determined.

When salts are dissolved in water the conductivity will increase because of the free ions that will be present. This solution is called an electrolyte and the formation of electrolytes lowers the freezing point as seen in Table 1.

Table 1. Freezing point lowering of water in °C as function of molality [10].

Compound	0,05 mol/ kg	0,10 mol/ kg	0,25 mol/ kg	0,50 mol/ Kg	0,75 mol/ Kg	1,00 mol/ kg	1,50 mol/ kg	2,00 mol/ kg	2,50 mol/ kg
NaCl	0,18 °C	0,35 °C	0,85 °C	1,68 °C	2,60 °C	-	-	-	-
CaCl$_2$	0,25 °C	0,49 °C	1,27 °C	2,66 °C	4,28 °C	6,35 °C	10,78 °C	15,27 °C	20,42 °C

A mixture of sodium chloride and water is very often used to prevent ice formation and to remove already formed ice. Figure 3 shows a binary system phase diagram for this.
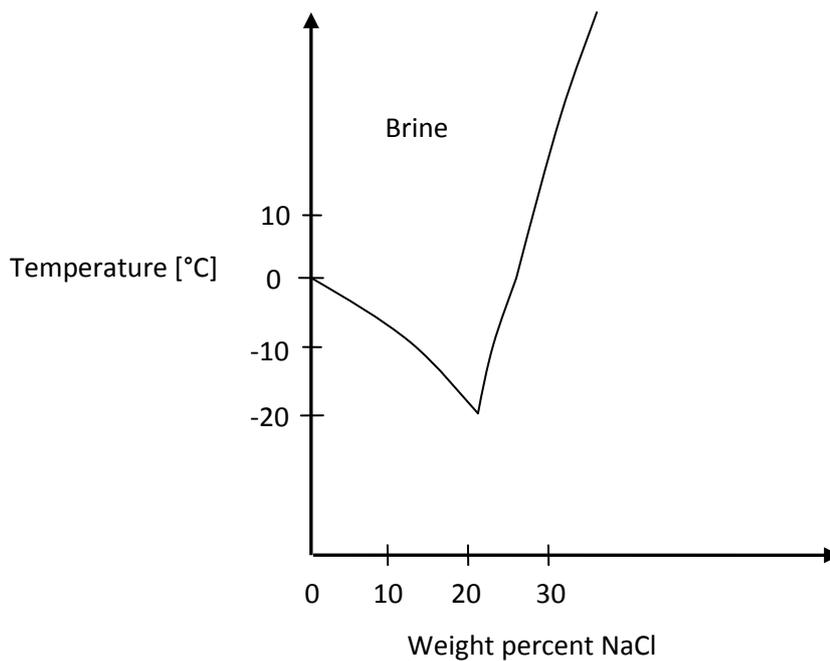
Figure 3. Phase diagram for a mixture of sodium chloride and water. Picture reproduced from [11].

From this diagram it is possible to determine the freezing point of a dilute mixture of sodium chloride and water by following the line from 0 °C to -21.2 °C. With this salt concentration and in temperatures above the thick line, all salt is dissolved in the solution and the solution will be in the brine area. Outside the brine area the mixture will contain unsolved sodium chloride. When 23.3% weight percent of sodium chloride is dissolved, the eutectic point is reached and the lowest possible freezing point is reached. When the eutectic point is reached it is not possible to dissolve any more salt into the water.

Passive methods to determine the freezing point

Passive methods of determining the freezing point of mixtures of water and salt implies a conductivity measurement. The conductivity can then be translated to a freezing point temperature value. The conductivity of a mixture of one salt, such as NaCl or $CaCl_2$, can easily be translated into a freezing point value.

Queeney [12] presents a comprehensive study of conductivity sensors. In order to follow the forthcoming experiments, a brief summary is given here.

Conductivity measurements implements one of three available methods of determining the conductivity of the mixture. The three methods commonly used to determine the electrolytic conductivity are:

- The two-electrode method is suitable for measuring low conductivities in relatively pure water.

- The four-electrode method is suitable for measuring mid to high ranges of conductivity and the four-electrode method is more foul-proof than the two-electrode method.

- The inductive method covers mid to high conductivity ranges. The inductive sensors are particularly resistant to fouling due to their measurement principle.

The electrolytic conductance is defined as the ability of a solution to carry electric current. The conductance is defined as the reciprocal to the resistance according to equation 1.

$$G = \frac{1}{R} \qquad (1)$$

$where$
$G = conductance\ in\ Siemens\ [S]$
$R = Resistance\ in\ ohms\ [\Omega]$

The conductivity is determined from measuring the electrolytic conductance under reference conditions with a specified electrode surface area and with the electrodes spaced at a specified distance as seen in equation 2.

$$\kappa = \frac{1}{R}\frac{d}{A} \qquad (2)$$

$where$
$d = electrodes\ spacing\ distance$
$A = surface\ area\ of\ electrodes$

The more ions that are present in a solution the higher the conductivity, but also the types of ions affect the conductivity. It would then be possible to assume that the conductance varies linearly with concentration. This is only true for very dilute solutions, and hence empirical correlations must be used to verify the results from the equation 2. In the diagram below it is seen how the conductivity varies depending on the amount and type of salt [12].
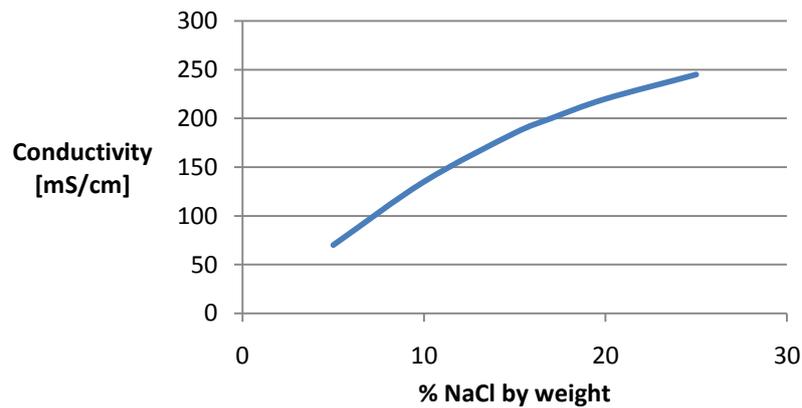
Figure 4. Conductivity vs. concentration at 25 ˚C (from [12]).

The conductivity is also temperature dependant why all conductivity readings are referenced to a temperature of +25° C. Temperature adjustments of all field measurements are necessary as it is shown in Figure 5.
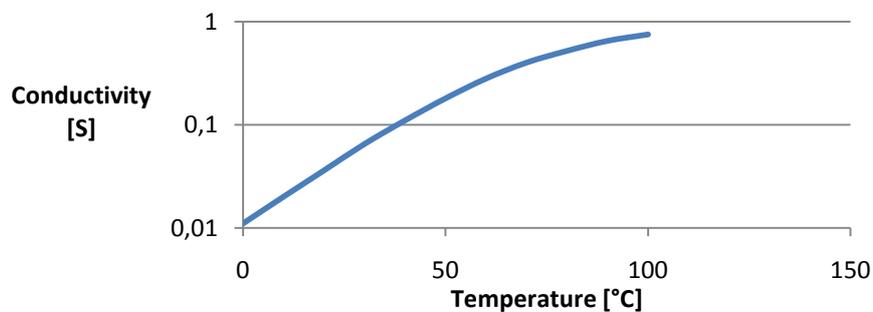
Figure 5. The Conductivity temperature dependence of pure water (from [12]).

Because of this temperature dependence, a temperature probe must be used to get the temperature of the fluid in order to calibrate the measured conductivity value to the reference temperature of 25° C.

There are a lot of manufacturers that provide sensors for road installations that implements conductivity measurements to determine the freezing point. A few examples are Quixote FP2000 [13] and the Vaisala ROSA system [14]. A detailed description of the passive sensors from specific manufacturers can be seen from [13] and [14] and from direct contacts with the manufacturers.

Active methods to determine the freezing point

Active methods of surface mounted freezing point sensors cools the surface fluid and detects the freezing point as the temperature when water releases heat during the formation of ice crystals. The sensors may utilize a cooler to lower the temperature of water until it forms ice crystals and freezes to ice. If the water temperature is monitored during this process a clearly identifiable change in the temperature versus time curve can be seen [8].

From the available patents from different suppliers of active sensors such as Boschung [15], Saab [16] and Quixote [17], the conclusion is that they use Peltier elements as the cooling equipment. A detailed description of Peltier modules and their usage can be found in [18].

Although Boschung and Saab use a Peltier module to force the phase change of the liquid on the road from water to ice, these two companies has, regarding to their patents, a different approach of determining the freezing point.

The Boschung sensor uses a temperature probe to measure the temperature of the fluid on the sensor surface and then detect the freezing point by looking at the temperature knee when the supercooled fluid starts to form ice crystals and releases its latent heat of fusion [15].
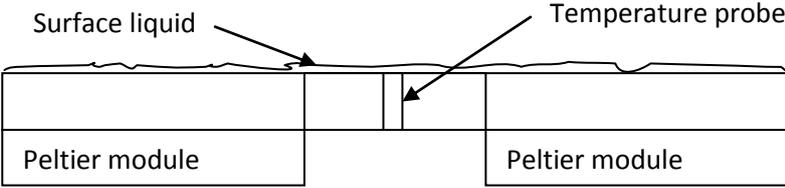
Figure 6. Simplified picture according to Boschung sensor patent

The Saab sensor has no temperature probe. The freezing point is instead found by looking at the change in Seebeck voltage when the fluid starts to form ice crystals and the supercooled fluid releases its latent heat of fusion [16]. The Seebeck voltage can be obtained when a thermoelectric device, such as a Peltier module, is exposed to different temperatures on each side [18]. The sensor is calibrated in order to get a correlation between the Seebeck voltage and the freezing point. This means that the Peltier module is both used as a cooler and as a detector.
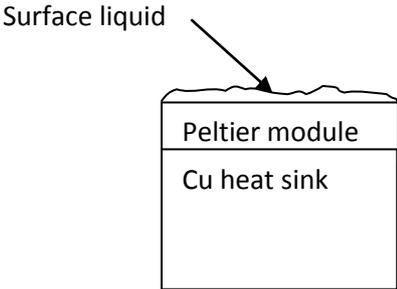
Figure 7. Simplified picture describing the Saab Frensor sensor

A very informative introduction to freezing point measurements with thermoelectric modules can be seen in [9].

Field performance of active and passive sensors

According to [19] both the active and passive sensors perform well under laboratory conditions and when these sensors are installed and tested in the field. As what could be understood from [19], the practical information from the sensors are useful and the sensors are resistant to wear and damage. The resistance to wear and damage for the passive sensors should be quite good as Quixote gives a lifetime warranty of their passive sensor [13]. From Saab and Boschung that provides active sensors, no extended warranty period could be found. They are supposed to follow standard warranty times of one (1) or two (2) years.

SETUP

In this experiment only sodium chloride was diluted in water since it is the most used freezing point depression substance [3]. A passive conductance sensor and an active freezing point sensor were used to determine the conductance and freezing point of a fluid. Mixtures of water and sodium chloride were given in weight percent.

Contaminations of one drop were diluted into 3 ml of tap water and the mixture was put on the sensors. The passive sensor was covered with 3 ml of the mixture and the active sensor was covered with 0.2 ml of the mixture. It is to be noticed that the experiment lacks the amount of data to statistically find the exact freezing point changes. The aim with the experiment is to study the sensors response to different contaminations on passive and active sensors. The experiment does not have the intention to present results regarding exact freezing point depressions and conductance changes.

Passive sensor

As passive sensor a two electrode sensor as in Figure 8 was used. The sensor had two semiconducting plastic rings with inner solid cylinder diameter 10 mm and outer ring 20 mm inner diameter with 4 mm thickness.
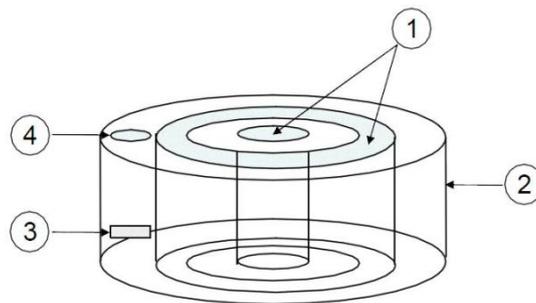
Figure 8. The passive sensor.
1 - semiconducting plastic rings,
2 - insulating plastic material with same heat transfer as asphalt,
3 and 4 - temperature sensors

The sensor was covered with three to four milliliter of fluid and the conductance was measured with an instrument that could detect resistance, capacitance, inductance and conductance. This instrument showed that the passive sensor had no inductance, but the resistance, conductance and capacitance varied depending on the fluid put on the sensor. The

small capacitance in the sensor is assumed to originate mostly from the 20 meters connection cable and was ignored. This specific sensor is not available on the market at the time of writing. The sensor is only used for evaluation purposes at this stage.

Active sensor

As active freezing point sensor the Saab Frensor was used, see Figure 9. The Peltier element is thermally connected to a copper body that will receive heat or cold depending if the sensor is cooling or heating the fluid on the other side of the Peltier element.
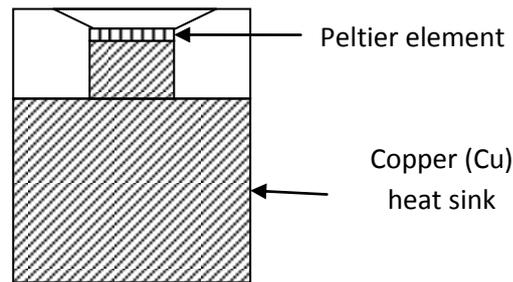
Figure 9. The Saab Frensor sensor.

The Frensor controller unit delivered the freezing points to a computer connected through a serial interface.

RESULTS

Table 2 shows the indications of the passive sensor at a constant environment temperature of 22.5 degrees centigrade:

Table 2. Passive sensor response to different dilutions of sodium chloride in tap water.

Sensor status	Expected freezing point [°C]	Conductance [μS]
Dry	-	29,2
Distilled water	0	35,5
Tap water	0	77,0
Water with 1% NaCl	-0,7	102,2
Water with 2 % NaCl	-1,4	108,0
Water with 10% NaCl	-6,6	133,0

The results from table Table 1 was correlated to the freezing points as seen in Figure 10. In this figure a straight line approximation was done for the freezing point region from tap water to 10 % sodium chloride. The approximation equation is y=-0.117x+10.19. As the data set is quite small at this time, a straight line approximation is sufficient for estimations of freezing points at this time. When larger datasets are available, a higher order approximation would probably be more suitable.
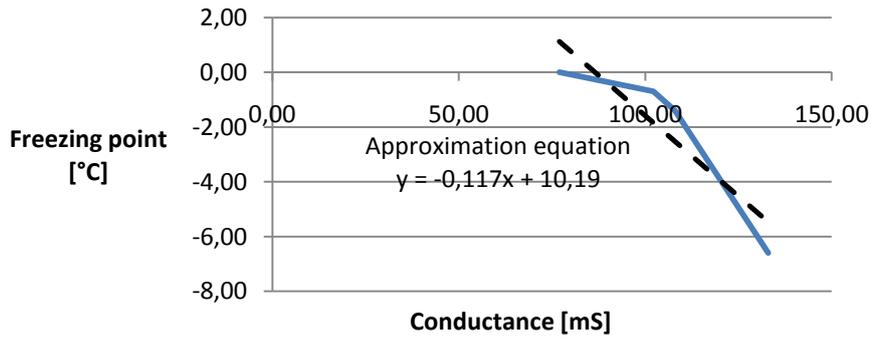
Figure 10. Correlation between freezing point and conductance for passive sensor. In the figure a straight line approximation is done and the fitting equation is shown.

The behavior of the passive sensor when it was contaminated can be seen in Table 3. In order to get rid of the problem with variations when measuring only the tap water conductance, the conductance was measured immediately before and after the contamination. The freezing point change is calculated according to the straight line approximation in Figure 10.

Table 3. Results from contamination of fluid on passive sensor.

Sensor status	Conductance change [µS]	Freezing point change [°C]
Change in conductance from tap water to tap water with 1 drop of glycol	-12,0	1,40
Change in conductance from tap water to tap water with 1 drop of ethylene alcohol	11,0	-1,29
Change in conductance from tap water to tap water with 1 drop of oil	46,0	-5,38

The same experiment was performed on the active sensor. From the sensor specification it was read that the sensor needs to be within 10 degrees centigrade from the freezing point in order to be able to detect freezing points. Therefore, the environment temperature of the active sensor body was held at +2 degrees centigrade. The results are in Table 4.

Table 4 . Active sensor response to different dilutions of sodium chloride in tap water.

Sensor status	Expected freezing point [°C]	Sensor reported freezing point [°C]
Dry	-	Dry
Tap water	0	-0,5
Tap water with 1% NaCl	-0,7	-1,8
Tap water with 2% NaCl	-1,4	-2,8
Tap water with 10% NaCl	-6,6	-8,6

The active sensor response to contaminations was examined by diluting contaminations into 3 ml of tap water and putting 0.2 ml of the contaminated fluid on the sensor. The oil was on top of water surface but during the experiment it was checked that oil was on the sensor surface. The results can be seen in Table 5.

Table 5. Results from contamination of fluid on active sensor.

Sensor status	Freezing point change [°C]
Change in freezing point from tap water to tap water with 1 drop of glycol	-2,4
Change in freezing point from tap water to tap water with 1 drop of ethylene alcohol	-1,9
Change in freezing point from tap water to tap water with 1 drop of oil	-0,2

Finally an environment friendly deicing fluid was tested. Ordinary table sugar was dissolved in tap water and the conductance of the water and sugar mixture was measured with the passive sensor. The freezing point of the sugar solution was also measured with the active sensor. The results are in Table 6.

Table 6. Results of freezing point depression with table sugar

Sensor status	Freezing point change with active sensor [°C]	Conductance change [µS] in passive sensor	Freezing point change [°C] for passive sensor
Tap water with 10% sugar	-0,7	41	-4,79

DISCUSSION

In this experiment sodium chloride was used. The results from other common road salts are expected to be similar as they are electrolytes.

The passive sensors can be made very robust due to their passive mode of operation. They have no areas where the sensor is heated or cooled. The sensor electrodes, that two electrodes and four electrode sensors have, are the only thing that connects the electronics with the anti-icing fluid. The sensor connections can be done in such a way that the sensors will be completely waterproof which is necessary when the sensor is installed in roads and runways. The inductive sensors have the advantage of not having any sensor elements in contact with the fluid. The inductive loops can be completely encapsulated in a suitable housing for extreme environments. Passive sensors may have problems with fluids that are mixed or polluted with unknown substances. The use of sugar as anti-icing material does not result in any ionic charges that can be detected by the passive sensors. Some conductivity sensors need a calibration of the deicing fluid being used in order to give correct freezing points. This may be a problem when different anti-icing fluids are used during a winter period because normally the sensors cannot be easily recalibrated.

Active sensors have a more complicated electronics and also the sensor physical construction requires significant technical skills to be made tough enough to withstand the environmental impacts and also the influence from heavy traffic flows. The sensor has parts that will be heated and cooled and the thermal effects of different materials must be taken in consideration when the design of the sensors is done. The electronics can be mounted on a roadside installation site instead of being installed in the road which will help give a good reliability of the active sensors. Due to the principles of active sensors their lifetime depends on the number of freezing point detections and their wear from traffic intensity. Every freezing point detection cycle involves a heating and cooling sequence of the sensor that may affect the material properties and decrease the sensor lifetime. A way of increasing the lifetime of active sensors would be to use a passive sensor in combination with the active sensor. The task for the passive sensor would then be to detect a wet surface and then initiate measurements with the active sensor. The number of freezing point detection attempts with the active sensor would decrease and the lifetime of the active sensor would increase.

The contaminations tested were of the type that is expected to be found on a road. From the experiments it could be seen that the passive sensor was very sensitive to contaminations and it even tended to show an increase of the freezing point for contaminations of alcohol and oil. The active sensor gave reasonable freezing points even if the sensor was contaminated. The small freezing point changes from contaminations of the solution on the active sensor were assumed to rely on the real freezing point change.

Sugar diluted in tap water does not result in any extra free ions in the mixture. When the sugar mixture was tested on the passive sensor it actually showed an increase of the freezing point instead of a conductance value that remained the same as for tap water. The active sensor detected, as expected, a freezing point depression when sugar was diluted in water.

The passive sensors are very robust and can reliable indicate if the road is dry or wet. The presence of chemicals may also be indicated, but the freezing point is not reliable because the contaminations can cause the conductivity to change in either direction indicating a freezing point depression or freezing point increase.

CONCLUSIONS

The conclusion is that passive sensors can be made more ruggedized than active surface mounted freezing point sensors and therefore can be assumed to have a very long lifetime. Active sensors have the advantage of measuring the real freezing point instead of a conductivity value that is translated to a freezing point. Another advantage of active sensors is that they can be used to detect the freezing point of environmentally safe freezing point depression fluids that have no conductivity such as sugar. Normally it is important to know the freezing point in order to be able to perform accurate road maintenance tasks that results in safe traffic and minimum influence on the environment. The experiments indicate that the only way to determine a correct freezing point of the road fluid is by using an active sensor.

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