BIRDS – Innovative sensor systems for detection of ice formation and freezing point temperature measurements

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Abstract

The freezing of water is an exothermic reaction, which means it releases heat, thus affecting the temperature of its surrounding. During a freezing event of a road surface high amount of heat energy will under a short period of time be released. By closely observing the temperature of a surface a freezing event can often be detected without any prior knowledge of the freezing point temperature. This principle is true also for roadways, thus making it possible to detect ice formation on roads by observing rapid changes in the temperature development. Two systems which are based on this principle are suggested.

A system named Passive Black Ice Infrared Detection System (Passive-BIRDS) has been designed to detect ice formation on roads. BIRDS use an infrared thermometer which makes it possible to detect rapid but small changes of the road surface temperature while being non-intrusive. Non-intrusive sensors have the advantage of easier maintenance and installation and do not require the maintenance personnel to operate on the actual road. The system can warn maintenance personnel of hazardous conditions due to ice formation as well as the driving public by the use of for example active warning signs.

A second system named Active-BIRDS uses the same principle as the passive system and also measures the temperature fluctuations with an infrared thermometer situated near the road. Active-BIRDS cools the road surface with an embedded cooling element until it reaches the freezing point. The freezing event is detected and the freezing point temperature of the road surface can be measured. This is a new method for measuring the freezing point temperature.

The systems could potentially be used for increased traffic safety and a cleaner environment by increasing the efficiency in winter road maintenance.

1. Introduction

Formation of ice is a dangerous road surface state condition. Predicting and detecting slippery conditions such as ice, hoar frost and snow formation is vital both for road users and road masters. Numerous sensors for detection of ice formation, and other road surface states, have been developed and implemented. (Casselgren, 2007; Pilli-Sihvola, 2006; Ogura, 2002)

The road surface temperature and the road surface freezing point are the two most important variables then forecasting road surface ice formation. Many methods for measuring the road surface temperature exists including resistance thermometers installed in the road surface or infrared thermometers installed on maintenance vehicles. The road surface freezing point temperature can be considered harder to measure and many attempts have been made including sensors measuring the conductivity of the surface moisture, sensors which freeze a small sample of road moisture and non contact sensors which use polarized light to measure. In a study by Gustavsson and Bogren (2007) it was concluded that a development of the present RWIS is needed. A most important aspect was to be able to have better knowledge of the road surface status and the local risk of slipperiness.

The present study addresses a new method for detecting ice and measure the freezing point temperature. Two systems which are based on the method will be described. The systems can measure the road surface temperature, detect ice formation and measure the road surface freezing point. The systems are based on commercial off-the-shelf (COTS) infrared thermometers which makes them cost-effective compared to other more complex systems. The systems have been tested successfully in a field trial and in climate chamber. More profound tests in real road environments will be conducted the winter of 2009-10. If successful the systems can be developed and used for improved traffic safety and increased efficiency in winter road maintenance. Further details about the methods behind the sensor are presented in Riehm et al. (2009).

2. Methodology

The methodology is based on two basic principles of thermodynamics:

(i) The freezing process of water does not always begin when the temperature (T) sinks to the freezing point of water (T_f). In practice the freezing seldom starts immediately when $T = T_f$. Instead the freezing of water often begins at a temperature significantly lower than the freezing point. This is the principle of super cooling.

(ii) A large amount of energy is released when water freezes.

As the temperature of a wet road surface sinks below the freezing point an ice nucleus has to form in order for the freezing process to begin. Normally the water can form an ice molecule spontaneously which acts as a nucleus for the surrounding water to freeze, but it could also be a change in pressure caused by turbulence which initiates forming of a nucleus. As T gets much lower than T_f the non-frozen water becomes more unstable and a smaller disturbance will be sufficient to cause the water to freeze. When freezing does occur latent heat is released and the large heat flow released will cause a sudden increase in temperature according to equation 1. The temperature will subsequently be equal to the freezing point as long as both water and ice are present in the system.

Water(liq) -> water(sol) + 333 J/g. (Equation 1)

The consideration of the two principles of thermodynamics provides a model of the road surface temperature during the process of freezing water which includes a sudden rise in temperature then the surface freezes. The model explains a very dynamic temperature pattern during the freezing process visualized in figure 1.

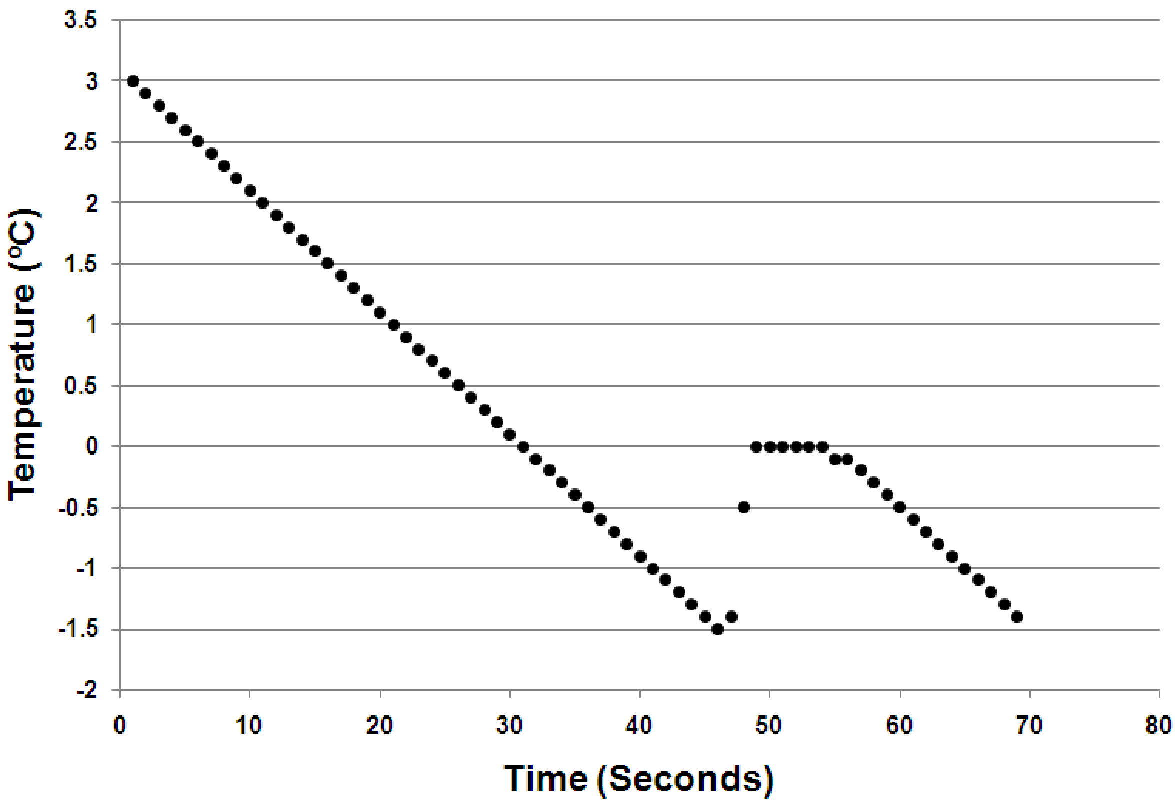

Figure 1. Model of the temperature pattern during ice formation

Under some circumstances the rise in temperature during ice formation will not occur. The most common of these circumstances is ice or snow already being present at the surfaces as the temperature sinks. In these cases the ice formation will start at the freezing point and will begin to form around the already existing ice nucleuses. Another cause could be that there is no humidity present at the surface.

To detect the sudden temperature in rise a thermometer which is responsive to s step-change in temperature has to be used. Resistance thermometers installed in the road surface will therefore not measure a temperature signal closely comparable to the model in figure 1. Secondly the temperature has to be measured on s small spot. If measuring over a spot the temperature signal will be smoothen out as freezing occurs at different moments in this larger area. To avoid both of these restrictions an infrared thermometer can be used. An infrared thermometer is a non-contact thermometer which measures the outgoing long wave radiation of an object which can be recalculated to a temperature by equation 2. The measurement principle of an infrared thermometer makes it extremely responsive to step-changes in temperature. The field of view of an infrared thermometer is decided by the choice of lens which makes it possible to choose a lens which makes the measurement spot small enough to detect the rapid changes in temperature during ice formation.

$R = \varepsilon\sigma T4$ (Equation 2)

ε = Emmissivity

σ = Stefan-Boltzmann's constant (5.67051*10-8 W * m–2 * K-4)

T = Temperature in degrees Kelvin.

The model of the temperature pattern during ice formation is very explicit due to the high positive derivate during a short time period which makes it easy to identify by an algorithm which continuously interprets the temperature signal. The algorithm could either search for high derivatives during certain conditions or use cross-correlation to detect the typical pattern. The infrared thermometer in combination with a detection algorithm is a method which potentially can be used for different kind of measurement systems.

3. System Design

3.1 Passive-BIRDS

Passive Black Ice Infrared Detection System (Passive-BIRDS) is based on the described method for detection of road ice formation as well as measuring the road surface temperature. The system is non-intrusive and consists of an infrared thermometer installed at the side of the road pointing towards the road surface. An ice detection algorithm is programmed to a micro-processor in the sensor head or uploaded to an existing logger at for example a road weather information station. To be able to distinguish the rapid changes in temperature the thermometer samples the temperature at high frequency over a close to circular measurement spot. The thermometer has to be carefully shielded to avoid dirt, snow and frost to cover the lens. No additional hardware is required.

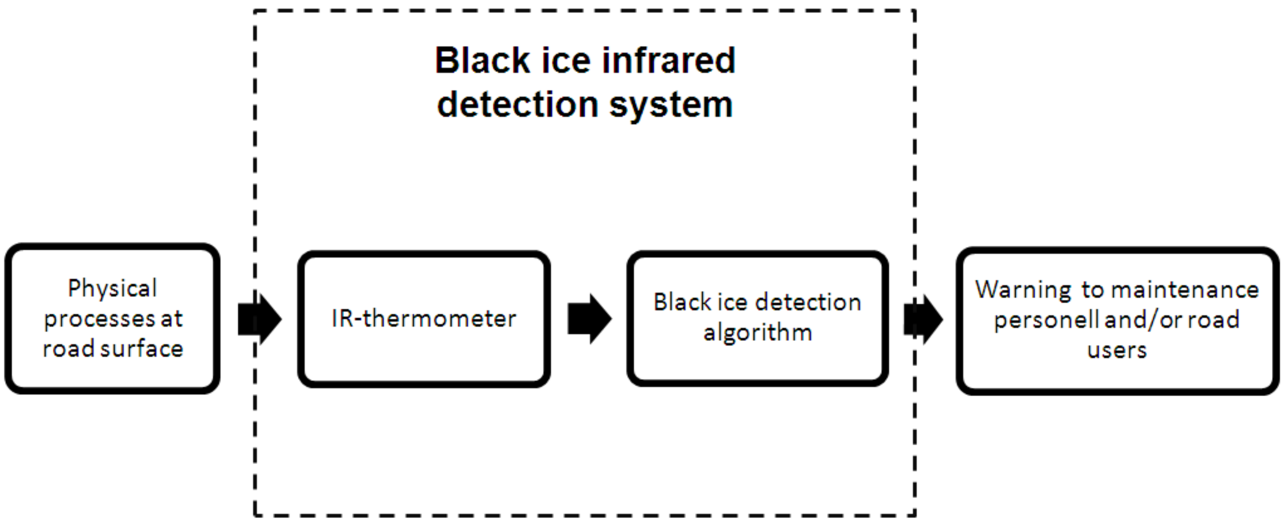

Figure 2. System-overview of Passive-BIRDS

The measured mean values of the road surface temperature can used as a road surface temperature measurement and be communicated to road masters. However, for such values to have any relevance the sensor has to be thoroughly calibrated and a correct value of the emissivity has to be used. Numerous methods for deciding the emissivity as well as reducing errors associated with the use of an infrared thermometer exist. The detection algorithm is situated within or near the sensor body of the infrared thermometer to avoid having to communicate data with very high frequency over a communication protocol. As the algorithm identifies an ice formation with one or several possible signal processing methods a warning can be send to the road weather information systems and thereby be visible for the road master who is responsible for the particular road stretch. If desired, a warning can also be send to road users by the use of active warning signs or variable speed limits. The system would be suited for installment on road stretches there restrictions on installments in the road surface exists or there is special reasons for not want to shut off traffic to install intrusive sensors such as bridges.

3.2 Active-BIRDS

Winter road maintenance personnel generally attempt to treat a road surface with deicing chemicals before it freezes and thereby avoiding slipperiness. To plan such actions a road surface temperature forecast is needed and many examples of models for forecasting road surface temperature exist. (Crevier, 2000) A road surface temperature model is however not sufficient to determine if the road is about to freeze, there is also a need for knowing the availability of moisture and the freezing point of the surface. If a previous deicing application is still efficient the freezing point temperature will be lower than 0ºC and a new application might not be needed. One of currently used methods for measuring the freezing point is to measure the conductivity in the surface and relate it to a concentration of for instance NaCl. This can then be related to a freezing point depression. The main problem with that method is that NaCl is by far not the only chemical at the road surface, traffic emissions also affect the freezing point and in many cases maintenance personnel mix different deicing agents such as $CaCl_2$ or sugar. Each unique chemical affects both the conductivity and the freezing point differently. Another used methodology is active techniques there a small sample of road surface moisture is frozen on the sensor which has been installed in the road. This methodology measures a true freezing point but it is often not representative for the road since dirt, slush and particles will cover the sensor.

Active-BIRDS is a further development from the passive system. It is an active system in the sense that it actually affects the road surface and in opposite to the passive system it is intrusive. The aim of active-BIRDS is to measure a true freezing point which is more representative to the road in general than other used methods. The active system is build like the passive but with the addition of a cooling element installed in the road body, figure 3. The cooling element, which is covered with asphalt or any other asphalt like material, cyclically cools the road surface to try to cause a freezing on the above road section. If the element succeeds in freezing the road section a circular area of about 5 cm in diameter is frozen. The principle of cover the cooling element with asphalt or another road like material will prevent problems like many other sensors have with wearing of the road and dirt.

An infrared thermometer is installed at the side of the road pointing at the cooled area and detects the time and temperature as the freezing is caused. Under some conditions, such as no deicing chemicals having been applied in the last days and temperature above zero degrees the system will be able to decide if the road is wet or not by freezing the surface far below the freezing point and try to detect a freezing, if no freezing occur the system can communicate that the surface is dry.

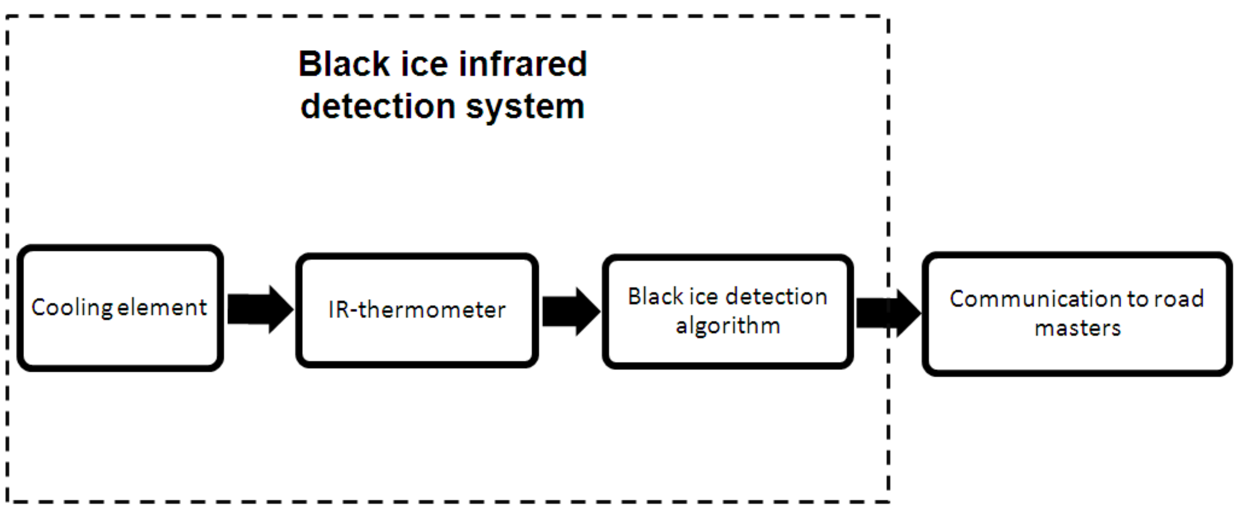

Figure 3. System-overview of Active-BIRDS

4. Results from trials with the systems

Passive-BIRDS has been tried for 3 months on a road surface stretch without traffic. During this period three natural ice formation events occurred which could be confirmed by an observer at the site.

A prototype of active-BIRDS has been built on a non-operated road stretch to make it possible to adjust and investigate the system in detail. The installed system is programmed to cool the surface once every hour. Preliminary results show that the system is able to measure the road surface freezing point and also give an indication of the amount of moisture at the surface. A typical temperature pattern during one cooling cycle can be seen in figure 4. It can be noted that it took the system 4 minutes to cool the surface from 9ºC to -2ºC there the water froze. Due to the water being super cooled before the freezing event the freezing point is measured after the heat have been released. In this case a freezing point of 0.7 ºC was measured. The surface had never been treated with any chemical and was clean; therefore a freezing point temperature of 0ºC could be expected. The error of at least 0.7 ºC is due to the emissivity have not been adjusted from factory setting. It can be noted that there is a second opportunity to read the freezing point temperature which occurs then the ice melts at 11 minutes.

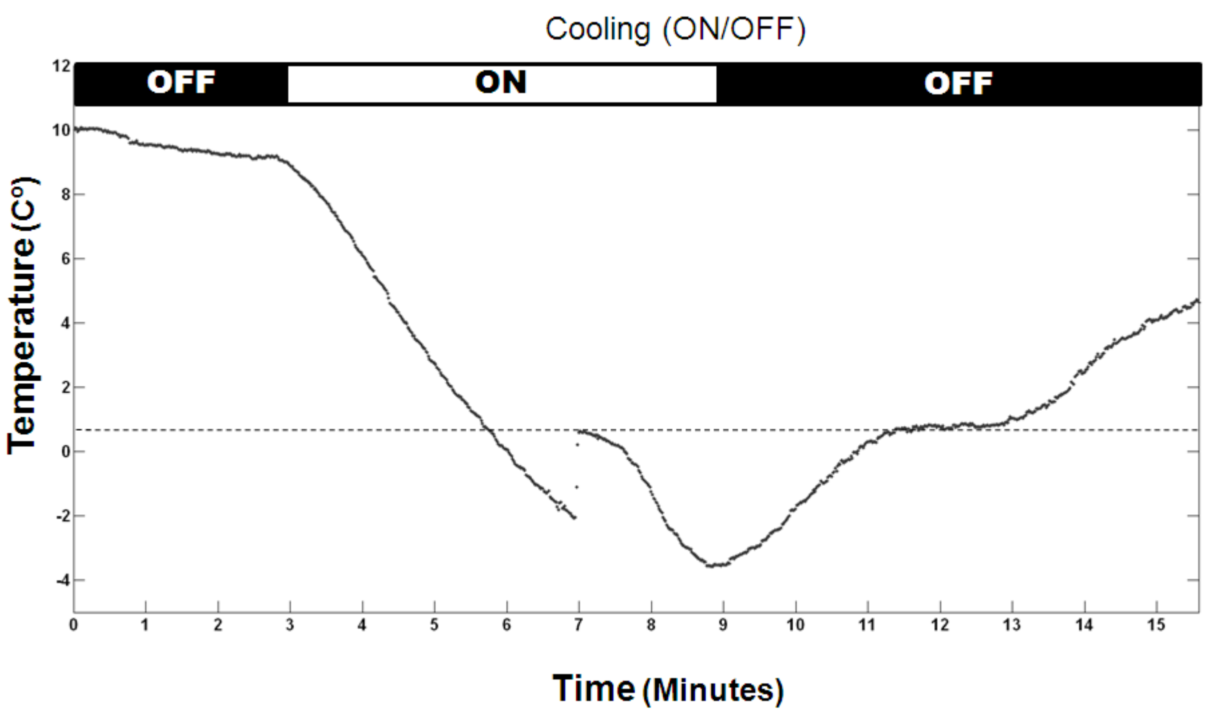

Figure 4. The temperature development during one cooling cycle with Active-BIRDS.

5. Conclusions

The principle of Passive-BIRDS simple and the cost of its hardware is low and it is a cost efficient system which could potentially aid to increase the efficiency in winter road maintenance as well as increasing traffic safety. Henceforth is the system cost efficient, non-intrusive and easy to install. Passive-BIRDS could be installed at existing road weather information stations or as a standalone system on for example bridges. The system measures the road surface temperature parallel with detecting ice formation. However, more research and development is needed to optimize the detection algorithm and adapt the sensor for the harsh road environment. Another important matter to examine is if it is possible determine other changes in road surface state from interpreting a high frequency temperature signal in combination with other instruments commonly available on a road weather information station, including hoar frost and snow.

Active-BIRDS have shown potential of measuring the road surface freezing point with the actual sensor at the side of the road and a cooling element embedded in the road body. It has also been concluded that the system could under some circumstances be used for determine if the road surface is wet or dry.

Both the passive and the active system will be tested in a real road environment clarify all potential opportunities and weaknesses. If development proves to be successful it is hoped that the systems can become a very cost effective option of measuring RST, detect certain road surface states and measure the freezing point. It is believed that the system can be combined with other variables measured at road weather stations to get more use of the station.

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