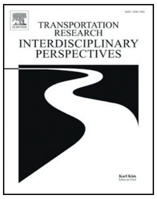
Transportation Research Interdisciplinary Perspectives 7 (2020) 100206

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: https://www.journals.elsevier.com/transportation-research-interdisciplinary-perspectives



A field study of sensors for winter road assessment

Tanita Fossli Brustad *, Aleksander Pedersen, Børre Bang

Faculty of Engineering Science and Technology, UiT The Arctic University of Norway, Lodve Langesgate 2, 8514 Narvik, Norway

ARTICLE INFO

Article history:
Received 18 March 2020
Received in revised form 7 August 2020
Accepted 15 August 2020
Available online xxxx

Keywords:
Winter road assessment
Sensor experimentation
Sensor data comparison
RCM411
MARWIS
Walabot

ABSTRACT

Winter road assessment is a research field with considerable progress over the last 10 years. Various sensors and methods have been tested and analysed, often in a laboratory setting, in order to come up with robust and valid assessment tools that can be used to warn the driver, road users in general, and maintenance personnel of critical conditions. In this paper we compare the field measurements of an RCM411 and a MARWIS sensor with each other and with previously performed laboratory experiments, we reflect on OBD-II as a tool in winter road assessment, and perform initial field tests with an experimental radar sensor. The results of the RCM411/MARWIS comparison shows significant correlation between our field experiments and the laboratory experiments, OBD-II appears to be fitting as a supplementary tool in the assessments, and the experimental radar tests uncovers a need for more investigation.

1. Introduction

Assessing road conditions during the winter season is important for safety and maintenance purposes. Knowing when and where road conditions are critical will help maintenance personnel do their job more efficiently (saving money) and can be used to warn other road users (increasing safety). Monitoring winter roads is essential in countries where the winter months are unpredictable in regards to weather and temperature. In Norway, accessibility on high mountain passes such as Saltfjellet, Bjørnfjell and Kvænangsfjell is often exposed to extreme weather conditions, leading to closed roads or formation of convoys driving in sections behind plow trucks. This type of conditions lead to inconveniences in transportation of goods and regular traffic and is also very costly for maintenance and scheduled deliveries not arriving on time. From (Bardal, 2018) a report was generated in 2019 regarding 17 such high mountain passes, including the ones mentioned previously. The report presents, among other things, how slower speeds and closed mountain passes effects the cost and loss of value for transportation. It is estimated that the social cost for these 17 mountain passes exceeds 90 million NOK, yearly. For most mountain passes, the amount of days where the road is closed or has convoys is increasing, and one mountain pass which stands out is Bjørnfjell with a total of 57 closings and 42 convoys during the 2017 season.

Today, research in winter road assessment mostly revolves around the use of sensors and cameras that analyse data collected from (and around) the road or from the car. Various sensors and methods have been proposed over the last 10 years e.g.: (Jonsson, 2011; Kawai et al., 2012; Omer and Fu, 2010) used camera images to classify surface conditions, the VehSense system in (Hou et al., 2017) combined a smartphone and OBD-II to detect vehicle skidding, (Jonsson and Riehm, 2012) utilized the latest infrared technology to measure road temperature, and (Häkli et al., 2013; Viikari et al., 2009) tested 24-GHz radar to recognize road conditions, to mention some. In addition there are sensors that have been developed specifically to collect important data for winter road assessment, two well known examples are RCM411 (Haavasoja et al., 2012) and MARWIS (Lufft, 2019). A number of laboratory experiments have been performed on these two sensors, see e.g. (Fay et al., 2018) or (Wåhlin, 2017), and in the last 5 years (2015–2019) the sensors have become more and more common as a tool in road condition research, either for collecting needed data (Laurinavičius et al., 2016; Sukuvaara et al., 2015; Ryguła et al., 2016), as a reference sensor (Schmiedel et al., 2019), or to study the reliability against sensors categorized as more reliable (Lovén et al., 2019). A motivation behind this work, where research material is scarce, is to carry out a practical long-distance test of multiple sensors exposed to a variety of conditions, ranging from sun and bare asphalt to rain, sleet, ice, and snow. Combining various road conditions with a stress test of the equipment can lead to another view on optimization and maintenance of the equipment. The goal of the research is to investigate the up-time of the sensors, during the stress test, and examine if the RCM411 and MARWIS sensors perform similarly in a field study setting, as they do in a laboratory setting, because this will strengthen the validity and broaden the knowledge of

---

* Corresponding author.
E-mail addresses: tanita.f.brustad@uit.no, (T.F. Brustad), aleksander.pedersen@uit.no, (A. Pedersen), borre.bang@uit.no. (B. Bang).

http://dx.doi.org/10.1016/j.trip.2020.100206

these two sensors, which are specifically developed for winter road assessment. The study has an explicit qualitative motivation and do not perform any quantitative test on the sensors.

As already mentioned, a variety of sensors have been tested for use in winter road assessment and more are being investigated currently. Just in the past year (2019) a number of papers have been published with focus on new sensors (e.g. an optical sensor in (Piccardi and Colace, 2019), capacitive sensors in (Döring et al., 2019), microphones in (Pepe et al., 2019), and a piezoelectric sensor together with an optical sensor in (Gui et al., 2019)) and new developments of known sensors/data, for instance vehicle sensor data (Yang et al., 2019) and camera images (Pan et al., 2019). So the search for "new" sensors is far from over, and experimental technology is still of interest to the field of study. Two desired properties of winter road sensors are that they should be cheap and not too large. Based on these properties, and our interest in experimental technology, our field research includes initial testing of a small and cheap radar sensor with much potential, the Walabot (Walabot, 2019). The EU Walabot model has a frequency range of 6.3–8 GHz, which is considerably less than the other radar sensors which has been utilized before. The reason for choosing a low frequency radar is its capabilities when dealing with harsh conditions. Low frequency radars (3–10 GHz) are less affected by contaminated air, such as dirt, condensation and vapour. The longer wavelengths of a radar such as the Walabot only strengthens the applications where turbulence and ripples are present (vibrations). Radar has other characteristics than the optical sensors and as far as the authors know there is no study to date which experiments with low wattage radars. During the practical long distance test the Walabot will also endeavour the same conditions as the other sensors, providing the study with a better understanding on how radar would perform compared to optical sensors. The main reason for testing more than one sensor in this research, and the reason for also including collection of data from the vehicle (with an OBD-II), is the possibility of using hybrid measurements in the future with various data that complement each other in a beneficial way.

In this paper we give a brief overview of the popular sensors, RCM411, MARWIS, and OBD-II, for winter road assessment, compare the field measurements of the RCM411 and MARWIS sensors with each other and with previously performed laboratory experiments, reflect on OBD-II as a tool in winter road assessment, and perform initial field tests with an experimental radar sensor.

The remainder of the paper is organised as follows. In Section 2 a description of the relevant sensors are given; RCM411, MARWIS, OBD-II, and Walabot. In Section 3 the sensor setup and test route are described and illustrated, together with key information regarding the analysis and comparison of the sensor data. Section 4 shows and discusses the results of the long distance stress test, and the comparison between RCM411 and MARWIS for segments of the extensive field test route against laboratory experiments, considers the usefulness of the OBD-II measurements, and reflects on the data from the experimental Walabot. And lastly, conclusions are drawn in Section 5.

2. Sensor descriptions

In this section a description of the sensors used in our field experiments is presented. The sensors are RCM411, MARWIS, OBD-II, and Walabot (radar). All can be seen in Fig. 1.

2.1. RCM411

Road Condition Monitor RCM411 (Haavasoja et al., 2012; Autioniemi et al., 2015; Teconer, 2015) (Fig. 1a) is an optical sensor based on spectral analysis that evaluates the surface condition by measuring the optical reflection signal on the road surface. The sensor, combined with a smartphone, analyse the data and gives information on surface conditions, friction, and water layer thickness, together with technical details regarding location and speed. In addition RCM411 uses an IR-thermometer (RTS411), supplied by Teconer, installed to the RCM411-frame. This thermometer gives feedback on air temperature and surface temperature in the same data package as the previous variables. RCM411 is designed to be mounted on the rear of a vehicle on a 50 mm tow ball, with the sensor pointing down towards the wheel track. Data from the sensor is transferred to a mobile phone using Bluetooth, then communicated to selected servers. This provides the opportunity to see real-time updates on surface conditions on a mobile phone app or online at https://roadweather.online. Raw data is also available for download on https://roadweather.online from the sensor you own.

2.2. MARWIS

Mobile Advanced Road Weather Information Sensor (MARWIS) (Lufft, 2018a, 2019) (Fig. 1b) is an optical sensor that captures the reflecting behaviour of the road surface at varying wavelengths to give feedback regarding the road conditions. In addition MARWIS has three other integrated sensors for measuring temperature and humidity. The data received from the sensor includes surface conditions, friction, water layer thickness, ice percentage, temperature (Surface, ambient, and dew point), and humidity (Relative and relative at ground temperature). MARWIS can be mounted on a truck or a car using a custom rack attached with magnets, and there are three ground-to-sensor distance options depending on the MARWIS model: 0.5 m, 1 m, or 2 m. Data from the sensor is transferred to a mobile phone using Bluetooth and can be viewed in real-time using the MARWIS app (Rau, 2017). The app has automatic upload of received data to a server (the ViewMondo-Server), which gives the opportunity of downloading, visualising, and analysing the measurements on the ViewMondo software platform (Lufft, 2018b).

2.3. OBD-II

On-Board Diagnostics, Second Generation (OBD-II) (OBD Solutions, 2019a, 2019b) (Fig. 1c) is a computer-based system monitoring the

(a) RCM411. (b) MARWIS. (c) OBD-II. (d) Walabot.

Fig. 1. The four sensors used in the field experiments.

performance of engine components. The system was originally designed to reduce emissions from vehicles and became a requirement in the US in 1996 on all newer vehicles. Later on other countries adopted similar laws, including Canada, parts of the European Union, Japan, Australia, and Brazil. The OBD-II system in a vehicle can be accessed via a Diagnostic Link Connector using a device called a scan tool or OBD-II adapter. Various information can be obtained from the diagnostics, e.g. status of the “Check Engine” light, diagnostic trouble codes, and hundreds of real-time parameters (i.e. Speed, RPM, coolant temperature, etc.). Most scan tools are compatible with third-party OBD software and mobile apps (e.g. via Bluetooth) that displays and saves information, and allows interaction with the OBD-II in the vehicle.

2.4. Walabot

Walabot (Walabot, 2019; SparkFun, 2018) (Fig. 1d) is a pocket-sized 3D imaging sensor that uses radio frequency technology to illuminate the area in front of it and sense the returning signals. The sensor supports short range scanning and distance scanning, with the possibility to extract 3D image data, 2D image slices, raw signals, and the sum of raw signals in an image. Data collected from the sensor is processed and sent through a USB cable to a host device (e.g. a Raspberry Pi). Depending on the model, the Walabot can be used in areas such as in-room imaging, in-wall imaging, object detection, motion sensing, and sensing of dielectric properties of materials. In addition many competitions have been held that focus on finding new use cases for the Walabot, some examples can be found at (Youtube, 2019).

3. Method

In this section the sensor setup and test route are described and illustrated. In addition, a description of key information connected to the analysis and comparison of the sensor data is given.

3.1. Sensor setup and field experiments

The sensor setup for collecting and saving data was done as follows: the RCM411 sensor sends data via Bluetooth to an Android phone and to servers showing the data online on https://roadweather.online, the MARWIS sensor sends data via Bluetooth to an Asus Zen Pad with an in-house developed app that shows real-time updates and saves the data, OBD-II data is collected via Bluetooth from an OBD-II adapter to a mobile app where real-time data is displayed and logged, and the Walabot sends data via USB to a Raspberry Pi that saves the data.

The sensor setup on the vehicle, seen in Fig. 2, was done in the following way: the RCM411 sensor was mounted on the tow ball pointing at the right wheel track, the MARWIS sensor was secured with a rack to the truck bed pointing at the center of the road behind the vehicle, and the Walabot sensor was attached below the back left passenger door pointing straight down at the wheel track. All sensors were mounted and configured according to their user manual instructions.

The field experiments were carried out in Northern Norway, Sweden, and Finland over 5 days, 26–28 of March and 2–3 of April 2018. A distance of 1729 km was covered stretching from Narvik to Vadsø, and back (the route is plotted in Fig. 3). The weather conditions ranged from sunny to heavy snow, with temperatures between −9 and +5 °C, and road conditions switching between icy, snowy, wet, moist, slushy and dry asphalt.

3.2. Analysis

For the long distance stress test, a focus was given to up-time of the sensors during the whole drive, which is important in order to consider the reliability of the sensors. The results were analysed by plotting the timelines for each sensor of when they were connected and measuring, and comparing the sensors against a reference measurement. By doing this it was possible to see gaps in the data when the sensors were disconnected, in order to get an overview of up-time and down-time along the entire test route.

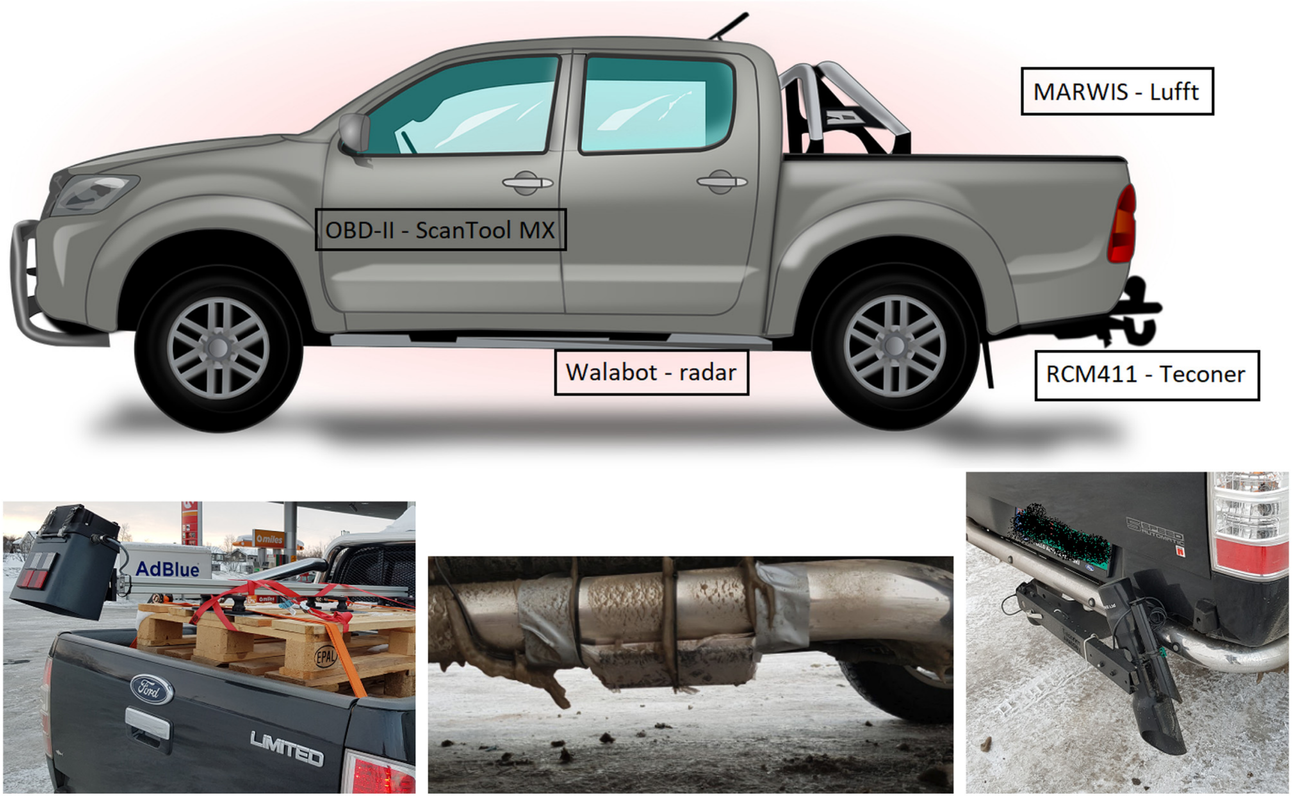


Fig. 2. Placement of the sensors on the car. Top image by OpenClipart-Vectors from Pixabay.

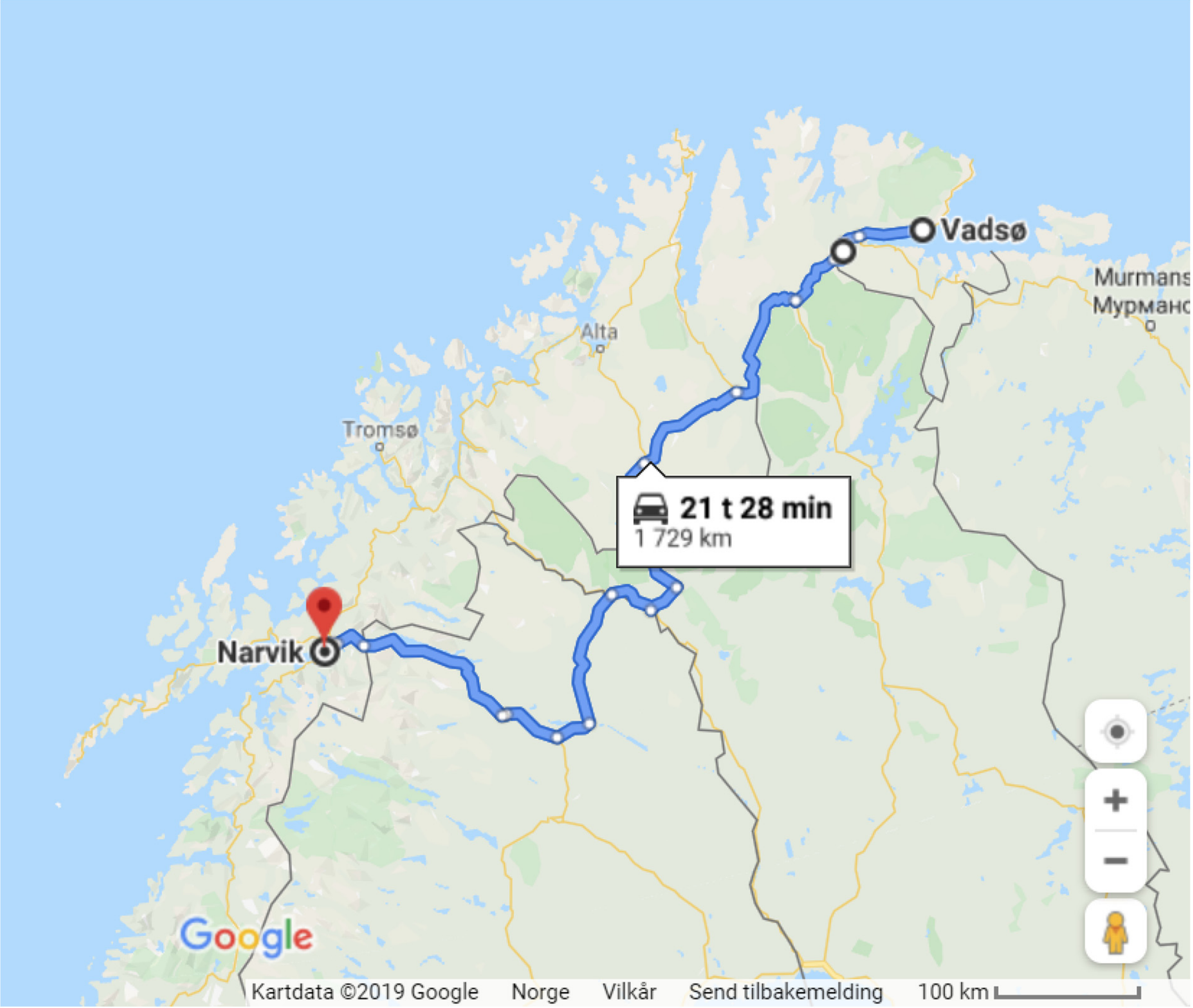


Fig. 3. The route, in Google maps, where the sensor testing was conducted.

In the comparison of the RCM411 and MARWIS sensors three variables were compared: friction, water thickness, and road temperature. The variables were chosen based on the awareness they are given in laboratory experiments, and because they were present in both sensors. The results were analysed by studying the graphs of the values obtained from certain stretches of road, chosen based on road conditions and sensor up-times. Comparisons of the RCM411 and MARWIS sensors have been performed a number of times in laboratory experiments ((Fay et al., 2018) and (Wåhlin, 2017) are good examples) so the consistencies between the laboratory experiments and field experiments are commented. Calibration of the two sensors was done using a grey asphalt plate, as in (Wåhlin, 2017), before experiments began. Four road segments were used in the comparison and analysis, one on the stretch from Narvik to Vadsø and three the other way, each with a timescale of 30 min (about 40 km in length), see Table 1. In the comparisons an important thing to keep in mind is that the sensors are not measuring in the exact same spot. The RCM411 measures behind the wheel track while MARWIS is near the middle of the lane. From experience we know that conditions can vary along the breadth of the lane, however, the authors consider the setup to be realistic given that the two sensors have different measurement area dimensions, so the sensors will never measure the exact same spot no matter where they are placed on the vehicle.

In the Walabot experiments the scan profile of the sensor was set to distance scanning with fast capture rate of low-resolution images, and the collected data was image energy (the sum of all image pixels' raw signal power). As with the RCM411/MARWIS comparison, the results were analysed by studying the graphs of the image energy, comparing them with each other for three segments with different surface conditions (Snow, ice, and dry/wet). In addition two phenomena regarding the measurement data were given a closer look: Walabot vs water/ice and Walabot vs vibration.

For the OBD-II an analysis and discussion is performed based on the available data from the sensor. The main question here being; what are the possibilities in using OBD-II data in winter road assessment?

Table 1
Description of the analysed road segments in the comparison between RCM411 and MARWIS.

Segment description			
Date	Location (on the stretch between)	Length [km]	Road conditions
March 28, 2018 10:10–10:40	Karasjok-Utsjoki	39.4	Mostly snow
April 2, 2018 16:45–17:15	Karasjok-Kautokeino	39.0	Dry and wet
April 3, 2018 09:45–10:15	Kautokeino-Enontekiö	40.3	Mostly ice
April 3, 2018 15:30–16:00	Kiruna-Narvik	38.0	Mixed

4. Results and discussions

In this section we present and discuss our main findings. First the stress test is presented, then we compare the RCM411 and MARWIS because of their similar measurement data and draw similarities to lab experiments, after that we consider the usefulness of the OBD-II measurements, and lastly we reflect on the data from the experimental Walabot sensor.

4.1. Stress test

From the motivational part we have already mentioned that this is a qualitative practical long distance test, which is imposing the stress factor on the total system, including car and sensor setup. The long distance drive was performed over 5 days that approximately corresponded to more than 20 h of driving with data recordings. In the stress test a focus was given to the up-time of the sensors. The up-time is the time a sensor has recorded data during a drive. In Fig. 4 the recorded up-time for RCM411, MARWIS, and Walabot is plotted, where each of the 5 days are presented in separate graphs. The reference measurements of the up-time for the 5 days are close to the RCM411 plots in each of the graphs. This conclusion is drawn based on the visualisation of the RCM411 data given at https://roadweather.online, where approximately 100% of the route is mapped. By using the RCM411 up-time as a reference point in the graphs it can be noticed that in general the up-time for the sensors in the stress test is satisfactory. MARWIS has some small gaps every now and then on 4 of the 5 days, and one larger gap on 27-03-2019. The reason for these gaps may be the loss of Bluetooth connection where small time frames are lost before the sensor is able to reconnect. Walabot has one day that stands out, 27-03-2019. Here the sensor is disconnected on a large part of the drive. The main reason for the disconnects in the Walabot, according to our experience, may be in the USB connection between the Walabot and the Raspberry Pi, where the USB plug needed to be kept stable to secure a connection.

4.2. RCM411 vs MARWIS

In this section friction, water thickness, and road temperature from RCM411 and MARWIS are compared between the sensors, and to laboratory experiments on the same sensors. A summary of the results can be found in Table 2.

4.2.1. Friction

The friction measurements, from RCM411 and MARWIS, for the four road segments, in Table 1, can be seen in Figs. 5, 6, 7, and 8, respectively. As an overall view of all four figures the first impression is that the two sensors have detected similar conditions in three of the four segments. However, MARWIS (red line in the graphs) has a tendency to produce spikes reaching min or max values, especially when the friction of the RCM411 (blue line in the graphs) is fluctuating.

In Fig. 5 with road conditions being mostly snowy, the friction behaviour, and also the values, are similar in both sensors. The biggest difference in this figure is, as commented on above, the spikes that MARWIS has in certain areas, reaching both highest and lowest values. The results from the laboratory tests in (Fay et al., 2018) and (Wåhlin, 2017) showed that MARWIS on average had lower friction on snow than RCM411, and that the type of snow did not matter for any of the sensors. Comparing the laboratory tests with our results we notice that this behaviour is only present for the first half of the graph, while for the last part the friction of RCM411 is on average lower. When it comes to the spikes in the MARWIS data the lab tests showed no such behaviour.

In Fig. 6 with road conditions being dry and wet interchangeably the friction behaviour is mostly alike for the dry parts. However, for the wet parts the friction values from MARWIS are considerably lower than RCM411 reaching the lowest value, 0.1, several times (RCM411 has its lowest value around 0.4). In the laboratory tests in (Wåhlin, 2017) the friction for both sensors when measuring on dry asphalt and water was fairly even between, 0.7–0.8, and 0.4–0.7, respectively. Comparing these results with our data shows that the RCM411 follows a similar pattern, while the MARWIS values go far below the lab values for wet conditions.

In Fig. 7 with road conditions being mostly icy the friction values are not closely related. The values for RCM411 are mainly between 0.3 and 0.6, while the MARWIS values are on average higher, between 0.5 and 0.8. The laboratory tests in (Wåhlin, 2017) showed that MARWIS was giving too high frictions on icy plates compared to RCM411. In these tests the friction measured by RCM411 was between 0.1 and 0.3, and MARWIS between 0.5 and 0.65. Although the lab tests were conducted on more slippery ice than our field tests, a conclusion can still be made that MARWIS has a

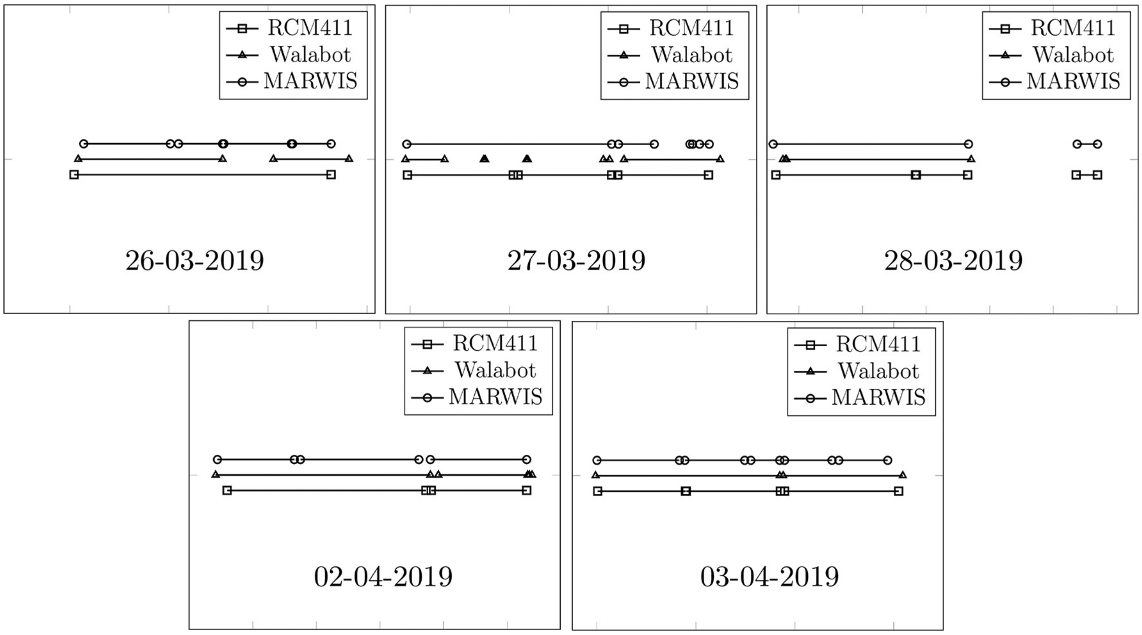


Fig. 4. Up-time for each sensor during five days of driving. Each graph represents one day. The gaps in the graphs are either a disconnect or a stop (the car has no keys in the ignition).

Table 2
A summary of the results presented in Section 4.2.

Conditions	Variables	Measurements	
		Field: RCM411 vs MARWIS	Lab: RCM411 vs MARWIS
Mostly snow	Friction	Similar behaviour and values. Some spikes in MARWIS	Similar behaviour. Lower values for MARWIS
	Water thickness	Zero for RCM411. On average 0.3 for MARWIS	Zero for RCM411, except on loose snow. Water detected for MARWIS on all types of snow
	Road temperature	Similar behaviour. Lower values for MARWIS	Calibration problems for MARWIS. Much lower values for MARWIS
Dry and wet	Friction	Similar behaviour and values on dry parts. Lower values for MARWIS on wet parts	Similar behaviour and values on dry and wet parts
	Water thickness	Similar behaviour. Higher values for MARWIS	Prone to over and under estimation. Affected by asphalt colour
	Road temperature	Similar behaviour and value	Not tested
Mostly ice	Friction	Values between 0.3 and 0.6 for RCM411. Values between 0.5 and 0.8 for MARWIS	Values between 0.1 and 0.3 for RCM411. Values between 0.5 and 0.65 for MARWIS
	Water thickness	Zero for RCM411. Between 0 and 0.25 for MARWIS	Zero for RCM411. Water detected for MARWIS
	Road temperature	Similar behaviour. Lower values for MARWIS	Not tested

tendency to show too high values for icy conditions when compared to RCM411, which is clearly seen in both experiments.

In Fig. 8 with mixed road conditions the friction behaviour is more complex. For the dry areas with maximum friction the two sensors agree for the most parts, but when other conditions appear MARWIS begins jumping between max and min friction almost everywhere, in contrast to RCM411 which has smaller changes. Taking into account the laboratory test from the three previous friction comparisons it can be argued that the MARWIS behaviour is similar, showing low values for water, high values for ice, and almost the same for snow and dry conditions. If in addition the spike phenomenon of MARWIS is taken into account then the differences between RCM411 and MARWIS on mixed road conditions is what would be expected.

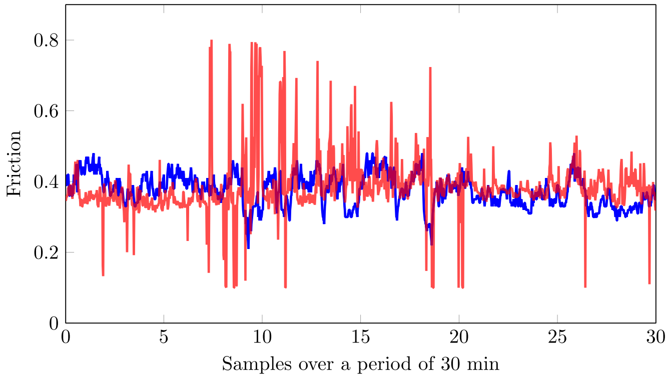


Fig. 5. A plot of the friction for RCM411 (blue) and MARWIS (red) on snowy road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the friction values.

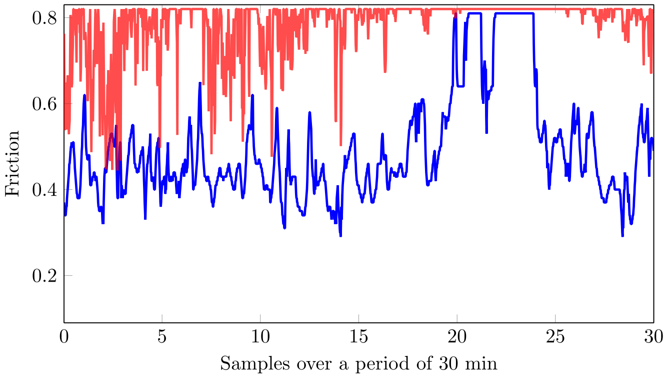


Fig. 7. A plot of the friction for RCM411 (blue) and MARWIS (red) on icy road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the friction values.

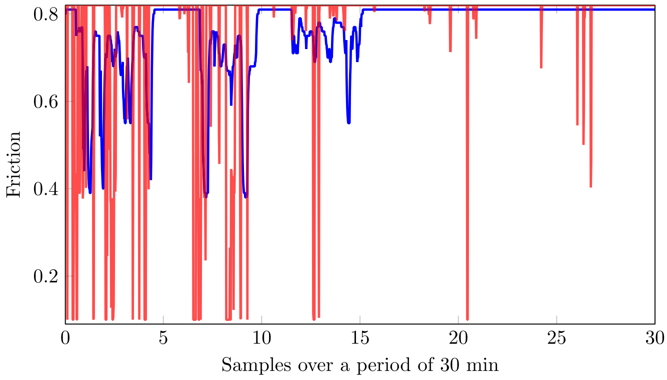


Fig. 6. A plot of the friction for RCM411 (blue) and MARWIS (red) on dry and wet road conditions interchangeably. The x-axis shows the samples along the road segment measured every second, and the y-axis is the friction values.

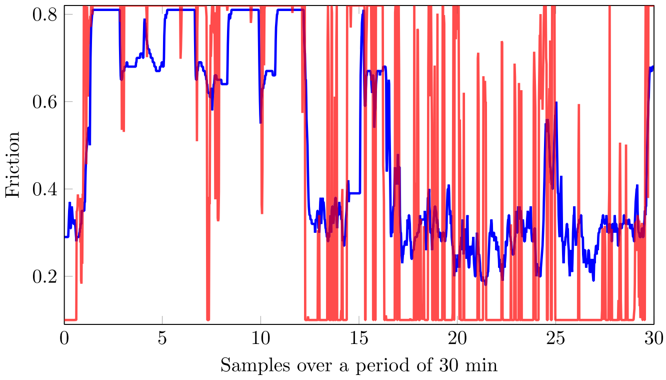


Fig. 8. A plot of the friction for RCM411 (blue) and MARWIS (red) on mixed road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the friction values.

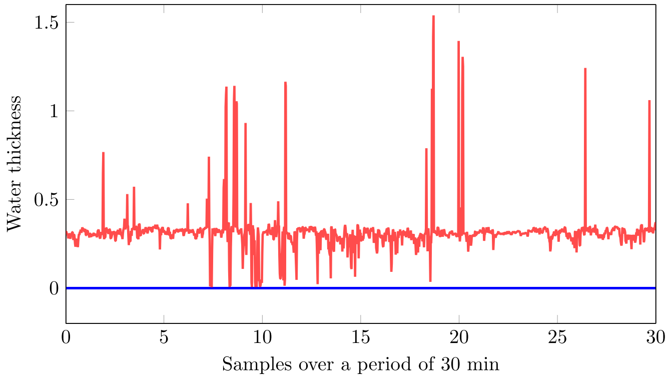


Fig. 9. A plot of the water thickness for RCM411 (blue) and MARWIS (red) on snowy road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the water thickness in mm.

A general conclusion to the friction test results is that the laboratory experiments compared to the field experiments had on average the same trend in the measurement data, which is a good sign that strengthens the reliability of the results in both experiments. As for the spiky behaviour of MARWIS in the field tests it is hard to pinpoint the exact cause without doing specific tests. Some explanations could be related to loss of data (where the value is just set to 0.1 or 0.8), placement and angle of the sensor, or vibrations while driving.

4.2.2. Water thickness

The water thickness measurements, from RCM411 and MARWIS, for the four road segments, in Table 1, can be seen in Figs. 9, 10, 11, and 12, respectively. At first glance of all figures the measurements from the two sensors do not seem to agree when it comes to water thickness. MARWIS (red line in the graphs) seems to show water a lot more frequently than RCM411 (blue line in the graphs), and with higher values.

In Fig. 9 with road conditions being mostly snowy the water thickness behaviour is somewhat similar in both sensors (staying almost constant), but the values are showing deviating results. The RCM411 has a constant water thickness of zero for the whole segment, while MARWIS shows an almost constant water thickness around 0.3 mm with some scattered values going higher or lower. In the laboratory experiments in (Fay et al., 2018) the water thickness on snow showed that RCM411 did not detect water for any snow types except loose snow, while MARWIS did detect water for all tested snow types. In addition the lab tests showed that MARWIS was more sensitive to changes in water thickness on a general basis, detecting small changes that RCM411 missed. By comparing the field results with the lab results, we conclude that the deviation in the values between the two sensors in the field tests are exactly reflecting the results from the lab tests, and even describes why MARWIS has scattered outliers.

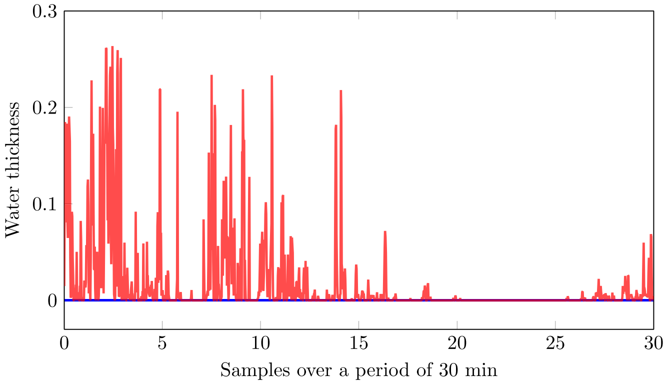


Fig. 11. A plot of the water thickness for RCM411 (blue) and MARWIS (red) on icy road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the water thickness in mm.

In Fig. 10 with road conditions being dry and wet interchangeably the water thickness behaves similar for both sensors, showing water in the same areas. When looking at the values, MARWIS measures higher water thickness than RCM411 almost everywhere on the road segment. From the laboratory tests in (Wåhlin, 2017) for wet asphalt the water thickness measurements are said to be unreliable for both sensors. Two experiments conducted in 2015 and 2016 gave different results regarding over and under estimations, and the colour of the asphalt affected the size of the error. By considering this and observing the results from the field tests we conclude that both sensors show water in the same areas, however, using the water thickness values has to be done with care because they can be inaccurate. In the field experiments RCM411 water thickness was on average about 1 mm below MARWIS (which also had some measurements reaching the max of 6 mm), that may have been caused by inaccuracy or because of the sensitive nature of MARWIS.

In Fig. 11 with road conditions being mostly icy the water thickness is dissimilar in both behaviour and value when comparing the sensors. RCM411 values are constantly zero while MARWIS values are fluctuating between 0 and 0.25. In the laboratory experiments in (Fay et al., 2018) the water thickness was not deliberately tested on ice, however, for one of the test cases the water froze almost instantly when applying it to the surface, and in these tests RCM411 did not detect water on the ice, while MARWIS did. This means that the behaviour of the water thickness for both sensors in the lab had an equal trend as the water thickness on snow. Comparing the field tests with the lab tests show that they behave

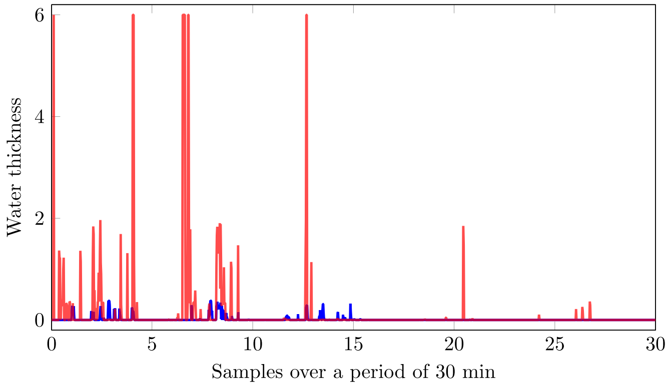


Fig. 10. A plot of the water thickness for RCM411 (blue) and MARWIS (red) on dry and wet road conditions interchangeably. The x-axis shows the samples along the road segment measured every second, and the y-axis is the water thickness in mm.

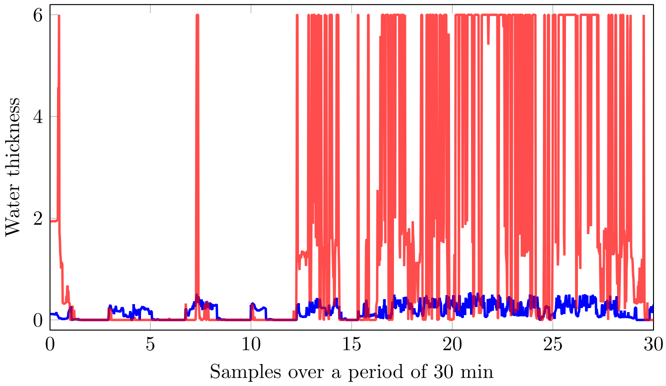


Fig. 12. A plot of the water thickness for RCM411 (blue) and MARWIS (red) on mixed road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the water thickness in mm.

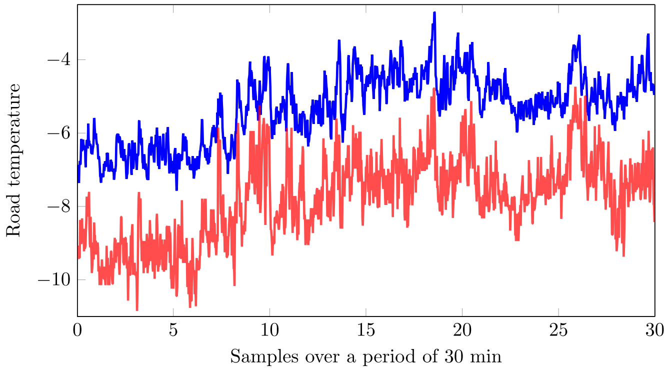


Fig. 13. A plot of the road temperature for RCM411 (blue) and MARWIS (red) on snowy road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the road temperature in Celsius.

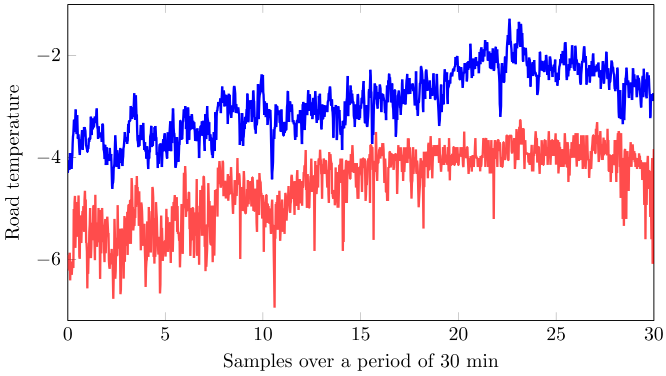


Fig. 15. A plot of the road temperature for RCM411 (blue) and MARWIS (red) on icy road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the road temperature in Celsius.

similarly, and that ice is a little more unpredictable than snow, reflected in the fluctuating values of MARWIS.

In Fig. 12 with mixed road conditions the water thickness is present on 2/3 of the segment for both sensors. By studying the conditions on the road segment an observation is made that RCM411 shows water thickness above zero on road parts where it measures icy conditions. This was not the case in Fig. 11, where RCM411 showed zero water on ice. For MARWIS the results are as expected since this sensor shows water for all previous conditions except dry asphalt. The only anomaly in the MARWIS data is that it often shows max value. Taking into consideration the lab results in (Fay et al., 2018) the tests show that icy conditions with a thin film of water is detected by both sensors. This means that the field results for RCM411 is probably correct if we conclude that the icy parts on this segment had water on it while the previous experiment on ice did not. There are no indications from the lab tests as to why MARWIS would show max value when RCM411 is not even close to its max value.

As a general conclusion we note that the field results for water thickness match the lab results. Some minor dissimilarities are detected, with the most prominent being the max value measurements (6 mm) of MARWIS. Possible reasons for this, as with the spikes in MARWIS friction data, could be loss of data (where the value is just set to 6 mm), placement and angle of the sensor, or vibrations while driving.

4.2.3. Road temperature

The road temperature measurements, from RCM411 and MARWIS, for the four road segments, in Table 1, can be seen in Figs. 13, 14, 15, and 16, respectively. The overall impression of the measurements in all figures is that the trend of the temperature is alike for both sensors. When it comes to the values it seems that RCM411 (blue line in the graphs) has higher values for some road conditions than MARWIS (red line in the graphs), and for other conditions the values are almost equal.

In Fig. 13 with road conditions being mostly snowy the behaviour of the road temperature is similar when comparing the two sensors, however, the values of RCM411 is constantly about 2 °C higher than MARWIS, for the entire road segment. In the laboratory test in (Fay et al., 2018) the road temperature measurements were showing large differences between RCM411 and MARWIS. The reason for these differences was problems regarding calibration of the MARWIS sensor, which caused MARWIS to display temperatures that were on average 7 °C colder than RCM411 on snowy conditions. In our field test it can be seen from the graph that we also obtained lower values for MARWIS, but only 2 °C lower on average, so in that sense the calibration was probably more accurate for our tests.

In Fig. 14 with road conditions being dry and wet interchangeably the road temperature is almost equal in both behaviour and value for the sensors. In some areas MARWIS has some lower values compared to RCM411, but the overall temperature is mainly alike on the road segment. The laboratory tests in (Fay et al., 2018) did not test road temperatures on dry or wet roads, so a comparison against lab results are not made. However, based on the results from the field tests, RCM411 and MARWIS seem stable in regard to each other when measuring road temperature on dry and wet surfaces.

In Fig. 15 with road conditions being mostly icy the road temperature for the sensors follows the same pattern as on snowy conditions. The behaviour is alike, but the values of RCM411 is on average about 2 °C higher than MARWIS. The laboratory tests in (Fay et al., 2018) did not test road temperatures on icy roads, so a comparison against lab results are not made here either. From the field experiments the comparison in the graph looks a lot like the comparison in Fig. 13, with slightly higher temperatures. From

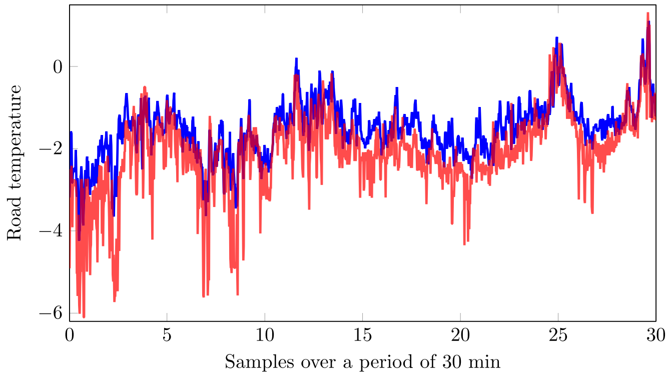


Fig. 14. A plot of the road temperature for RCM411 (blue) and MARWIS (red) on dry and wet road conditions interchangeably. The x-axis shows the samples along the road segment measured every second, and the y-axis is the road temperature in Celsius.

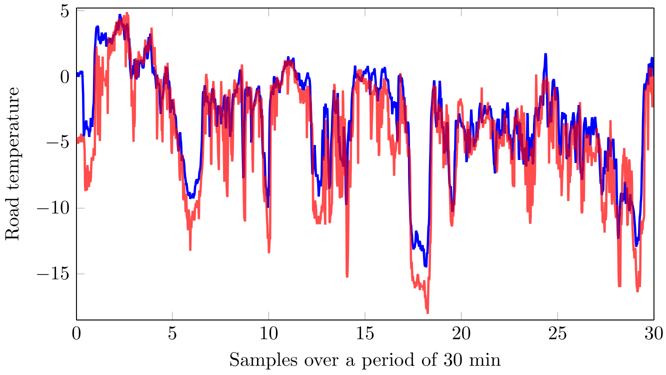


Fig. 16. A plot of the road temperature for RCM411 (blue) and MARWIS (red) on mixed road conditions. The x-axis shows the samples along the road segment measured every second, and the y-axis is the road temperature in Celsius.

this, a conclusion that the road temperature from the sensors act equally on snowy and icy roads is plausible.

In Fig. 16 with mixed road conditions it appears that the road temperature follows the same trend as the three previous tests. In some areas the values are similar (here we expect dry or wet asphalt) and in other areas MARWIS shows lower temperatures than RCM411 (here we expect snow or ice covered asphalt). As a whole the sensors seem consistent when measuring road temperature, and we notice that the analogous spikes in the MARWIS data from the friction and water thickness experiments are not present in the road temperature measurements.

The general conclusion to the road temperature field tests is that for dry and wet roads the temperature is mainly equal for the sensors, while on snowy and icy roads the temperature from MARWIS is on average, in our case, 2 °C lower than the temperature from RCM411. An explanation for the deviation between the RCM411 and MARWIS values on snow and ice could be the difference in placement of the sensors, or calibration of the sensors.

4.3. OBD-II

The data collected from the OBD-II is in itself not directly suitable for winter road assessment. However, the data can be used as a supplementary tool to other sensors in the assessment. From previous research OBD-II has been utilized together with a smartphone to detect vehicle skidding (Hou et al., 2017), it has been modified and expanded on to create a device that allows customization by the end-user to detect road conditions (Enriquez et al., 2012), and it has been used together with a smartphone, and road and air temperature to detect slippery roads (Robinson, 2012). The common factor in these three examples is that the OBD-II data is only one part in a larger integrated system, relying on algorithms with multiple input to evaluate road conditions. OBD-II can give information regarding the vehicle that other sensors know nothing about, for instance, vehicle wheel speed, vehicle acceleration, steering wheel angle, and brake pressure, to mention some relevant variables. The information collected from the vehicle can be a great addition in winter road assessment, both in order to increase useful data and maybe reduce the need for other sensors, hence saving costs. A relevant example that should be mentioned within this topic is (Gustafsson et al., 2001) and their idea of a virtual sensor. Although they do not directly use the OBD-II, they still collect various data from the vehicle and run that through an algorithm to estimate the friction between road and tire, and the tire pressure. In our field experiments the OBD-II data has not been used to evaluate road conditions momentarily. Data has been collected sequentially for the whole test route, so future work may include tests involving OBD-II measurements.

4.4. Walabot

The Walabot sensor is an experimental radar sensor which we have decided to test as a tool in winter road assessment. The reason for choosing the Walabot sensor is its small size and low cost, as well as it being a radar. This is interesting since radar technology has not been tested extensively for winter road assessment, which in theory it should be suited for given that radar is not dependent on sight, being less affected by snowy or foggy conditions where, for instance, optical sensors have a problem. The sensor is tested against itself on three segments with different road conditions (snow, ice, and dry/wet). Fig. 17 shows the comparison of the three measurements; snowy conditions in blue, icy conditions in grey, and dry/wet conditions in red. From the figure we see that the measurements are very similar, and it is hard to draw a conclusion based on this one result alone. Research on the use of radar in winter road assessment has been done before: two examples are (Häkli et al., 2013) and (Viikari et al., 2009). In these two papers, the backscattering properties of various surfaces are studied to estimate road conditions. The conclusion drawn in both papers is that the radar is suitable to assess the road under certain conditions. Two important conditions are the incidence angle of the radar and the surface roughness. In our field experiments the incidence angle was zero in all tests, whereas in the two papers (Häkli et al., 2013; Viikari et al., 2009) a large angle (50–80°) was shown to highlight different conditions to a greater extent than small angles. In addition, small changes in the surface roughness was proven to cause large variation in the measurements. Based on these results and Fig. 17 it can be concluded that more tests are required to say something constructive about the abilities of the Walabot to determine road conditions, however, we have opted for including these measurements to show some preliminary results concerning the setup and use of the Walabot.

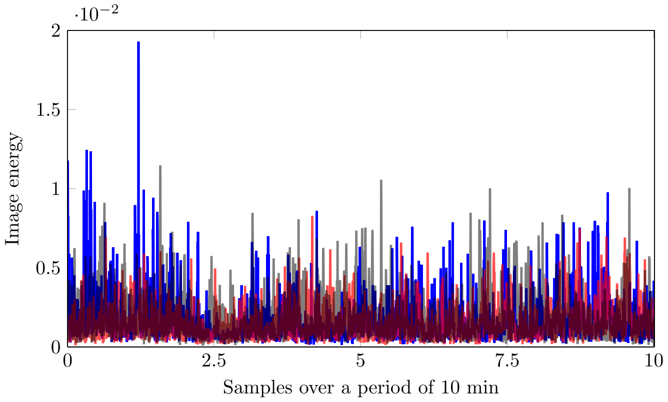


Fig. 17. A plot of Walabot energy for snowy (blue), icy (grey), and dry/wet (red) road conditions. The x-axis shows the samples along the road segment measured between 4 and 5 times every second, and the y-axis is the image energy.

When analysing the Walabot data, after the experiments were completed, we noticed two phenomena caused by outside forces which were affecting the Walabot measurements. The first phenomenon is that the Walabot sensor was sensitive to water and ice covering the sensor's casing. In Fig. 18 the Walabot image energy (red) can be seen along a road segment, where in the middle of the segment RCM411 measures water (blue) on the asphalt. The figure shows that a little while after driving through water the image energy values drop significantly, as a consequence of water, or possibly ice (air temperatures were around −1 °C), covering the sensor. About 5 min after this incident the sensor was cleaned and values returned back to normal. The example given in Fig. 18 was one of the most prominent examples of water or ice affecting the sensor in this way. No other Walabot data showed the same decrease in value, so a conclusion here is that conditions can disrupt the Walabot measurements if the setting is just right, however, this does not happen often and can be prevented by considering the placement and containment of the sensor. As mentioned, the reasoning in using Walabot in the experiments was

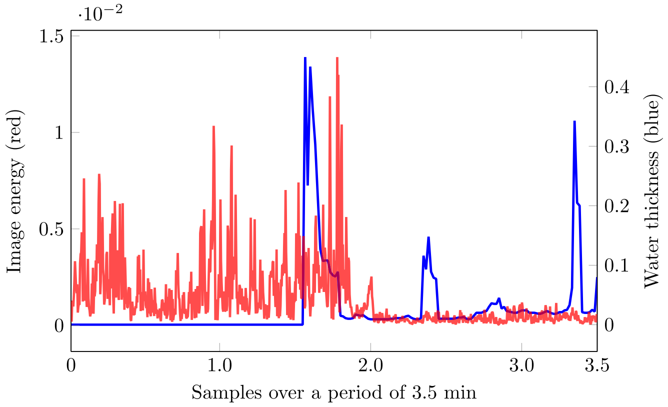


Fig. 18. The Walabot energy (red) being affected by RCM411 water thickness (blue). The x-axis shows the number of samples during the measured period, between 4 and 5 samples every second for the Walabot and every second for the RCM411. The y-axis is the image energy for the red graph (Walabot) and water thickness (mm) for the blue graph (RCM411).

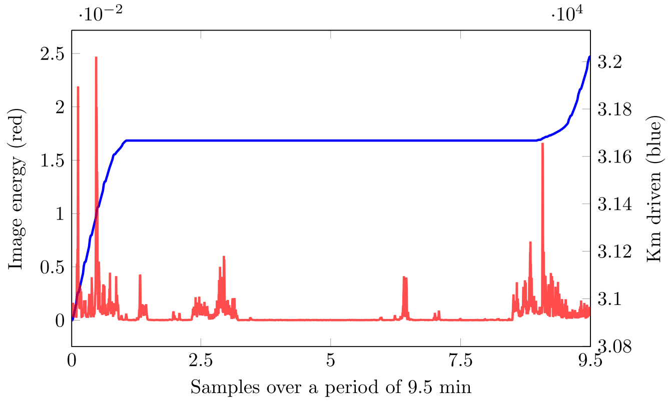


Fig. 19. The Walabot energy (red) being affected by car vibration. The x-axis shows the number of samples during the measured period, between 4 and 5 samples every second for the Walabot and every second for the RCM411. The y-axis shows image energy for the red graph and km driven (from RCM411) for the blue graph, where the flat area indicates that the car is at a standstill.

that radar could be a useful addition to optical sensing as it does not depend on sight. But as the field experiment show, snow/slush build-up on the sensor is detrimental to its sensing capabilities, and it has some of the same problems as optical sensors in harsh conditions. However, a better configuration, both mechanical and electronic, would be interesting to investigate.

The second phenomenon of outside forces affecting the Walabot measurements was the sensor's sensitivity to vibrations of the car. An example can be seen in Fig. 19 where the values of the Walabot data (red) approaches zero when the vehicle is at a standstill (represented by the blue line which is km driven). The small ripples in the area where the car is parked shows people getting out of the vehicle or in to the vehicle, and the door is opened and closed. In addition to this example, all other stops along the test track showed similar behaviour from the Walabot. As the Walabot was configured to measure total image energy, with fast capture rate, the Doppler component of the signal is strongly connected to the effects of vehicle speed and vibrations. Change in surface conditions, should give a change in the backscatter component of the signal, but preliminary analysis show that it is so small compared to the effect of vibrations that it may be impossible to isolate it in this data set. Further investigations should consider other configurations of the radar, and the possible use of multi-resolution signal analysis (wavelet/mra) for extracting relevant parts of the radar signal.

The conclusion on using Walabot as a tool in winter road assessment is that, with the settings and placement of the sensor, and the fact that we collected image energy, the sensor did not give unambiguous answers. Reading previous research on the topic gave us reason to believe that more experiments with other parameters can give different, and possibly better, results. In addition, the behaviour of the sensor data led to a hypothesis that the sensor only return vehicle vibrations, and nothing else. If other results would have appeared given that, for instance, raw data was collected instead of image energy or the incidence angle was changed is a question for future work, which would be interesting to investigate.

5. Conclusion

In this paper we performed field experiments with four sensors, RCM411, MARWIS, OBD-II, and Walabot, for use in winter road assessment. A stress test was conducted with focus on up-time of the sensors. RCM411 and MARWIS were tested against each other, and compared to laboratory experiments. OBD-II data was collected for future us as a supplementary tool in the road assessment. And initial tests for the experimental Walabot sensor were carried out.

The stress test showed that RCM411 was the most reliable sensor in relation to up-time and was thus used as the reference measurement to analyse MARWIS and Walabot. MARWIS had some small gaps in the measurements where the Bluetooth connection was lost before being reconnected. While Walabot had some large gaps on one of the test days, which according to our experience was probably because of an unstable USB connection between the Walabot and the Raspberry Pi.

The comparisons between RCM411 and MARWIS showed that the field tests followed the same pattern as the laboratory experiments, for all three variables (friction, water thickness, and the limited data on road temperature). Regarding the values of the data, RCM411 returned predictable values (as expected from the knowledge of the test route, and the lab tests) in all experiments, while MARWIS had predictable behaviour but experienced spikes in the values for friction and water thickness, possibly explained by loss of data, placement and angle of the sensor, or vibrations. Overall, the results from the RCM411/MARWIS experiments were consistent with the lab results, and the sensors showed similarities between themselves, although MARWIS had some incorrect readings and seemed to be more sensitive to small changes in the road conditions, especially for water thickness.

In the OBD-II analysis previous research showed that OBD-II data could be used as a supplementary tool in winter road assessment, mainly to detect slippery road surface. The research combined data from the OBD-II with data from other sensors, running them through an algorithm to evaluate road conditions. Results were positive and interesting, and gave good arguments for the use of OBD-II data in winter road assessment. In our project OBD-II has not been applied in the assessments yet, however, data from the test route exists and may be considered for future work.

Lastly, the Walabot tests, and previous research, indicated that more experiments should be conducted before giving a conclusion on the suitability of the sensor in winter road assessment. From the results in the field experiments different surface conditions did not appear considerably different in the Walabot data, and it was also discovered that the sensor was sensitive to water/ice covering the casing, and to vibrations caused by the vehicle. In future work controlled experiments should be performed where several parameters are changed, in order to increase the test set and give a more accurate measurement.

Data availability

The data used to support the findings of this study is available from the corresponding author upon request.

Acknowledgement

This research was in part financed by the Interreg-Nord project Winter Road Maintenance “WiRMa” [project ID 20201092].

References

Autioniemi, J., Autioniemi, M., Casselgren, J., Konttaniemi, H., Sukuvaara, T., Ylitalo, R., 2015. Intelligent Road. Technical Report. Lapland University of Applied Sciences, Luleå University of Technology, Finnish Meteorological Institute.

Kjersti G. Bardal. Fremkommelighet på høyfjellstrekninger. Technical report, Nordland Research Institute, 2018.

Döring, Jakob, Tharmakularajah, Lakshan, Happel, Jakob, Krieger, Karl-Ludwig, 2019. A novel approach for road surface wetness detection with planar capacitive sensors. J. Sensors Sens. Syst. 8, 57–66 01. https://doi.org/10.5194/jsss-8-57-2019.

Enriquez, D.J., Bautista, A., Field, P., Kim, S., Jensen, S., Ali, M., Canopnr, J.Miller., 2012. Can-obd programmable-expandable network-enabled reader for real-time tracking of slippery road conditions using vehicular parameters. 2012 15th International IEEE Conference on Intelligent Transportation Systems, pp. 260–264 Sep.

Fay, Laura, Akin, Michelle, Muthumani, Anburaj, Shi, Xianming, 2018. Quantifying Salt Concentration on Pavement: Phase II – MARWIS and Teconer Laboratory Sensor Evaluation. Technical Report. Western Transportation Institute, Montana State University June.

Gui, Kang, Ye, Lin, Ge, Junfeng, Cheikh, Faouzi Alaya, Huang, Lizhen, 2019. Road surface condition detection utilizing resonance frequency and optical technologies. Sensors Actuators A Phys. 297, 111540. https://doi.org/10.1016/j.sna.2019.111540 ISSN 0924-4247. http://www.sciencedirect.com/science/article/pii/S0924424719300998.

Gustafsson, Fredrik, Persson, Niclas, Drevö, Markus, Forssell, Urban, Quicklund, Henrik, Löfgren, Mats, 2001. Virtual Sensors of Tire Pressure and Road Friction. Technical Report 2376. Linköping University, Automatic Control.

Haavasoja, Taisto, Nylander, Juhani, Nylander, Pauli, 2012. Experiences of mobile road condition monitoring. Proceedings of SIRWEC 2012. Helsinki, Finland May.

Häkli, J., Säily, J., Koivisto, P., Huhtinen, I., Dufva, T., Rautiainen, A., Toivanen, H., Nummila, K., 2013. Road surface condition detection using 24 GHz automotive radar technology. 2013 14th International Radar Symposium (IRS). vol. 2, pp. 702–707 June.

Hou, Y., Gupta, A., Guan, T., Hu, S., Su, L., Vehsense, C.Qiao., 2017. Slippery road detection using smartphones. 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), pp. 1–5 June.

Jonsson, P., 2011. Classification of road conditions: From camera images and weather data. 2011 IEEE International Conference on Computational Intelligence for Measurement Systems and Applications (CIMSA) Proceedings, pp. 1–6 Sep.

Jonsson, Patrik, Riehm, Mats, 2012. Infrared thermometry in winter road maintenance. J. Atmos. Ocean. Technol. 29 (6), 846–856.

Kawai, S., Takeuchi, K., Shibata, K., Horita, Y., 2012. A method to distinguish road surface conditions for car-mounted camera images at night-time. 2012 12th International Conference on ITS Telecommunications, pp. 668–672 Nov.

Alfredas Laurinavičius, Donatas Čygas, Audrius Vaitkus, Tomas Ratkevičius, Matas Bulevičius, Darjušas Mučinis, and Andrius Baltrušaitis. Research of snow melting materials performance efficiency for road winter maintenance. Transport, 31: 322–332, 07 2016. doi: https://doi.org/10.3846/16484142.2016.1211551.

Lovén, Lauri, Karsisto, Virve, Heikki Järvinen, Mikko J., Sillanpää, Teemu Leppänen, Peltonen, Ella, Pirttikangas, Susanna, Riekki, Jukka, 2019. Mobile road weather sensor calibration by sensor fusion and linear mixed models. PLoS One 14 (2), 1–17 02. https://doi.org/10.1371/journal.pone.0211702.

Lufft, 2018a. USER Manual MARWIS/StaRWIS. https://www.lufft.com/download/manual-lufft-marwis-starwis-en/.

Lufft, 2018b. ViewMondo User's Manual. https://www.lufft.com/download/manual-lufft-viewmondo-en/.

Lufft, 2019. MARWIS Specifications. https://www.lufft-marwis.com/en_US/specifications.

OBD Solutions, 2019a. What is obd?. Online. https://www.obdsol.com/knowledgebase/on-board-diagnostics/what-is-obd/. (Accessed 21 October 2019).

OBD Solutions, b. STN1100 Family Reference and Programming Manual. https://www.scantool.net/downloads/98/stn1100-frpm.pdf. (Accessed 21 October 2019).

Omer, R., Fu, L., 2010. An automatic image recognition system for winter road surface condition classification. 13th International IEEE Conference on Intelligent Transportation Systems, pp. 1375–1379 Sep.

Pan, G., Fu, L., Yu, R., Muresan, M., 2019. Evaluation of alternative pre-trained convolutional neural networks for winter road surface condition monitoring. 2019 5th International Conference on Transportation Information and Safety (ICTIS), pp. 614–620 July.

Pepe, Giovanni, Gabrielli, Leonardo, Ambrosini, Livio, Squartini, Stefano, Cattani, Luca, 2019. Detecting road surface wetness using microphones and convolutional neural networks. Audio Engineering Society Convention 146 (March. http://www.aes.org/e-lib/browse.cfm?elib=20326.

Piccardi, Armando, Colace, Lorenzo, 2019. Optical detection of dangerous road conditions. Sensors 19, 1360 03. https://doi.org/10.3390/s19061360.

Rau, Peter, 2017. User Manual - MARWIS App. https://www.lufft.com/download/manual-marwis-ios-app-en/.

Ralph Robinson. Slippery road detection and evaluation. Technical report, University of Michigan, Transportation Research Institute, 2901 Baxter Road, Ann Arbor, MI 48109, 2012.

Ryguła, A., Honkisz, M., Maczyński, A., Brzozowski, K., Konior, A., 2016. Mobile system for recording road weather conditions. Arch. Transp. Syst. Telematics 9 (3), 42–45.

Schmiedel, Bernhard, Gauterin, Frank, Unrau, Hans-Joachim, 2019. Study of system layouts for road wetness quantification via tire spray. Automot. Engine Technol. 4 (1), 63–73 Jun.

SparkFun, 2018. Getting started with walabot. Online. https://learn.sparkfun.com/tutorials/getting-started-with-walabot?_ga=2.140213947.929731503.1570004485-127684519.1570004485. (Accessed 2 October 2019).

Sukuvaara, Timo, Mäenpää, Kari, Ylitalo, Riika, Konttaniemi, Heikki, Petäjäjärvi, Juha, Veskoniemi, Juho, Autioniemi, Matti, 2015. Vehicular networking road weather information system tailored for arctic winter conditions. Int. J. Commun. Netw. Inf. Secur. 7, 60–68 04.

Teconer, 2015. Winter maintenance of roads and runways. http://www.teconer.fi/en/winter.html.

Viikari, V.V., Varpula, T., Kantanen, M., 2009. Road-condition recognition using 24-GHz automotive radar. IEEE Trans. Intell. Transp. Syst. 10 (4), 639–648 Dec.

Wåhlin, Johan, 2017. Laboratory Tests of Optical Road Condition Sensors, 2015 and 2016. Technical Report, Statens Vegvesen, Norway; Trafikverket, Sweden; Vejdirektoratet, Denmark; Tiehallinto, Finland, Vegagerdin, Iceland and Landsverk Faroe Islands. November.

Walabot, 2019. Walabot - Technical Brief. https://walabot.com/docs/walabot-tech-brief-416?type=pdf.

Yang, Choongheon, Yun, Dukgeun, Kim, Jinguk, Shin, Sungpil, 2019. Estimation road surface temperature variation using commercial vehicle ambient sensor. IOP Conference Series: Materials Science and Engineering 603, 022027 09. https://doi.org/10.1088/1757-899X/603/2/022027.

Youtube, 2019. Walabot programmable 3D sensor. Online videos. https://www.youtube.com/channel/UCdQcnXMiEGizQvPODZIwvBA/videos. (Accessed 3 October 2019).