10.14 LABORATORY AND FIELD TEST RESULTS FROM A PAVEMENT SENSOR

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ABSTRACT

Road surface conditions must be monitored constantly and classified accurately (icy vs. snowy vs. dry etc.) to give decision-makers the information they need to carry out highway winter maintenance effectively. In the USA and around the world, thousands of automatic road weather stations (RWSs) are installed at roadsides to serve this purpose. Since information on road "slipperiness" is critical for driver safety, the RWS information must be as accurate as possible.

Vaisala has designed and introduced a new model of pavement sensor to market. It measures surface water thickness on the pavement using an optical reflection method. The information on water layer thickness leads to improved accuracy in the measurement of de-icing chemical concentration in the surface solution. In addition, the new optical reflection method enables snow detection based on high reflection value. Both of these factors improve the detection accuracy of pavement conditions.

This paper describes the results of laboratory and field tests that were conducted using the Vaisala pavement sensor, described above, attached to a road weather station. Several different salt concentrations were measured in the laboratory with an accuracy of 10% or better. The water layer thickness measurement results are presented in the range of 0...8 mm.

In the field tests, the surface state reported by the RWS was compared against human observations. The road surface was classified as icy, snowy, frosty, wet (& chemical), moist (& chemical) and dry. The observations were collected over several winter periods in Columbus, Ohio, and in Finland. The Columbus results (total of 496 samples) show 97% agreement with the human observer.

1. INTRODUCTION

In most countries experiencing adverse surface conditions due to winter weather, it has become common practice to use information gathered by automatic road weather stations to assist in winter maintenance decision-making. A range of sophisticated sensor technologies are available to meet the needs of road maintenance organizations. However, new applications of intelligent transport technologies – such as automatic message boards, weather controlled speed limits and bridge sprayers – set even higher accuracy requirements for the measurement of surface conditions.

Most commercial pavement condition sensors work on the principle of the qualitative detection of the presence of water or ice. From the point of view of actual driving grip, however, it is essential to know the amount of the frozen substance on the road surface. Laboratory testing has shown that the grip between tire and asphalt is dangerously reduced when the layer of ice exceeds 50 micrometers in thickness, Nicolas (1996). Although the actual grip will depend to a great extent on the condition of the tire and on the roughness of the asphalt, this laboratory result suggests that a small amount of ice can create slippery conditions. During freezing rain of typical intensity (1 mm/h), it takes only a few minutes for 50 micrometers of ice to accumulate.

Another important factor affecting tire grip is the concentration of de-icing chemical compounds in the frozen water. The freezing process of a solution containing a de-icing chemical and water begins at the so-called *liquidus* temperature and continues, if the temperature continues to drop, until the solution is completely frozen. The ice crystals in the frozen substance will mainly be pure ice that does not contain the de-icing chemical; the remainder of the frozen substance will therefore contain a higher proportion of the de-icing chemical. The conclusion to draw is that a solution containing water and a de-icing chemical does not freeze at a single temperature, Turunen (1997). Consequently, a road with a salty surface will become slippery only gradually as a function of decreasing temperature. The temperature at which freezing begins is usually expressed as the ”depression of freezing point”, DFP.

Since the thickness of ice and concentration of salt (de-icing chemical) on the road surface are essential factors in identifying slippery conditions, there is a clear need to measure these factors reliably and accurately. In this paper we present the results of laboratory tests that were performed on the Vaisala DRS511 road surface sensor, which is equipped with an optical detector for measuring water layer thickness. The sensor can also directly detect the presence of snow or frost, which frequently cause slippery conditions.

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In the experimental portion of the tests, we attempted to answer the question: How reliably can the pavement condition be measured on a given section of road surface? To answer this question, we set up a test system that generated pavement condition observations from two independent sources: Vaisala DRS511 sensor technology and independent human observers.

2. OPERATING PRINCIPLE AND THE LABORATORY TESTS

The Vaisala DRS511 pavement sensor is a multi-sensor block that can measure e.g. temperature, pavement condition and surface salinity. The sensor is 84 mm long and 30 to 38 mm wide. The height depends on the model: 50 to 75 mm. The sensor design features open-end carbon fiber electrodes and optical fibers. These are molded into a solid sensor block made of a special epoxy compound with thermal conductivity and emissivity properties that closely match those of the road surface. The sensor and the parameters it measures are shown in Figure 1. The optical coverage measurement, discussed in more detail later, is marked with a red circle.

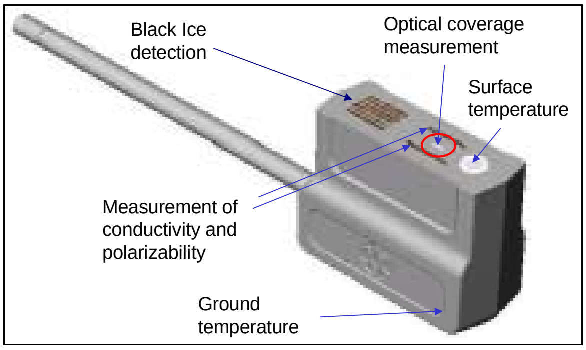

Figure 1. Vaisala DRS511 multi-sensor block

The DRS511, when connected to a Vaisala ROSA road weather station, reports the following:

- surface temperature (°C)
- ground temperature (°C)
- pavement condition (DRY, ICY, etc.)
- water layer thickness (mm)
- chemical concentration (g/l) and chemical amount (g/m^2)
- depression of freezing point (°C)

The DRS511 classifies the pavement condition according to the following categories:

- Dry
- Moist
- Moist & Chemical
- Wet
- Wet &Chemical
- Snowy
- Frosty
- Icy

2.1 Measurement of water layer thickness

The DRS511's optical detector works on the principle of light reflection: it detects the light reflected from the top surface of the water layer resting on the sensor. In essence, it is a typical optical distance sensor that has been modified for installation in the road pavement, flush with the road surface. With water layer thicknesses of 8.0 mm or less, the response of the optical detector is strongly dependent on the distance between the optical detector and the surface of the water layer. Figure 2 illustrates the principle.

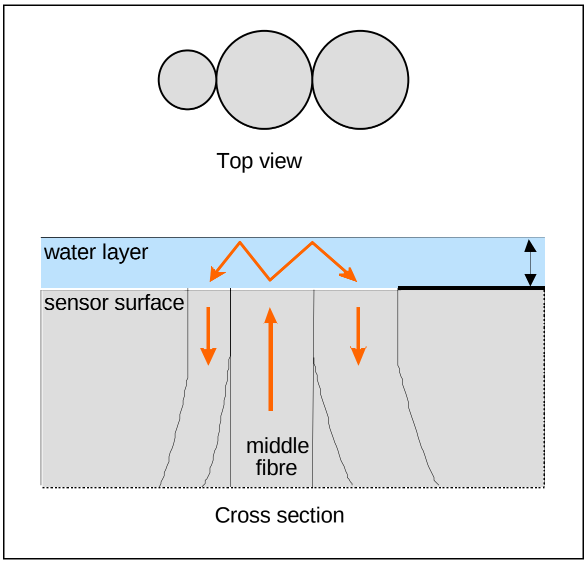

Figure 2. Water and ice layer thickness measurement principle at work in the DRS511 sensor.

Figure 3 shows the response of the optical detector as a function of actual water layer thickness. The data was generated in the laboratory by allowing the water layer to evaporate slowly, reducing its thickness, which was measured and recorded accurately using a microscope. We can conclude that in ideal conditions the optical detector's measurement accuracy is ±0.1 mm in the water thickness range of 0.0 to 1.0 mm.

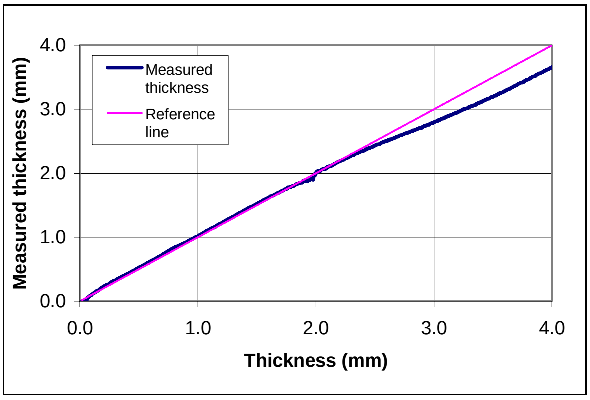

Figure 3. Water thickness measurements up to 4 mm.

Figure 4 displays the results of an identical laboratory test on the measurement of water layer thickness up to 8.0 mm. The results show very good agreement with the reference value, and also show that the measurement range can be extended to 8 mm.

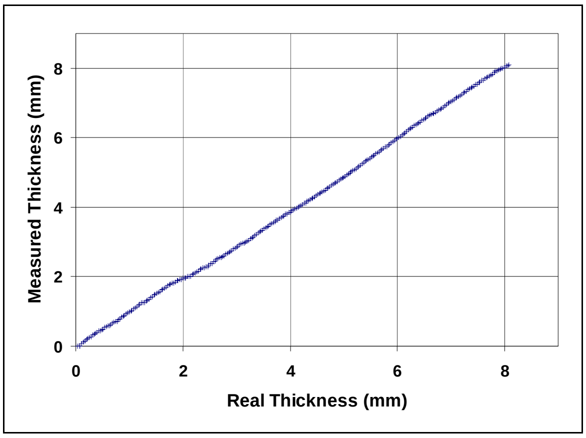

Figure 4. Water thickness measurements up to 8 mm.

The optical properties of ice are very similar to those of water. This is especially true of clear ice (black ice). Therefore, the DRS511 optical detector is able to measure the thickness of ice on the road surface although, in comparison with water layer thickness measurement, measurement accuracy is somewhat reduced due to the slight difference in optical properties.

The optical reflection properties of snow and slush are different from those of water. Therefore, the DRS511 cannot measure actual snow thickness on the road surface, although it does accurately detect the *presence* of snow directly on the road surface. The snow detection is based on the high reflection signal coming from the snow on top of the sensor. The capability to detect snow on the road is significant advantage: if it is snowing, the DRS511 can indicate whether the snow stays on the road or whether it drifts away due to high winds.

2.2 Measurement of salt concentration

The amount of salt on a wet road surface can be calculated (in units of g/m^2) on the basis of the electrical conductance of the solution on the road surface. The salt concentration of the solution is then obtained by dividing the amount of salt by the thickness of the water layer (the relationship between the salt concentration and the depression of freezing point is precisely known). Consequently, by measuring the salt amount and the water layer thickness it is possible to arrive at a reliable estimation of the freezing properties of the road surface.

Figure 5 shows the results of a laboratory measurement test conducted at 0°C for salt concentration, depression of freezing point and water layer thickness. Solutions of pure water and water/NaCl with NaCl concentrations of 2.5, 5.0, 10, 20, 40, 80, 160, and 200 g/l were applied to the sensor in sequence. The peaks in the data were caused by changing the solution on the sensor, and should be ignored. We can conclude from the data that an accuracy of better than 10% in the calculation of salt concentration and depression of freezing point can be achieved with a calibrated DRS511 sensor.

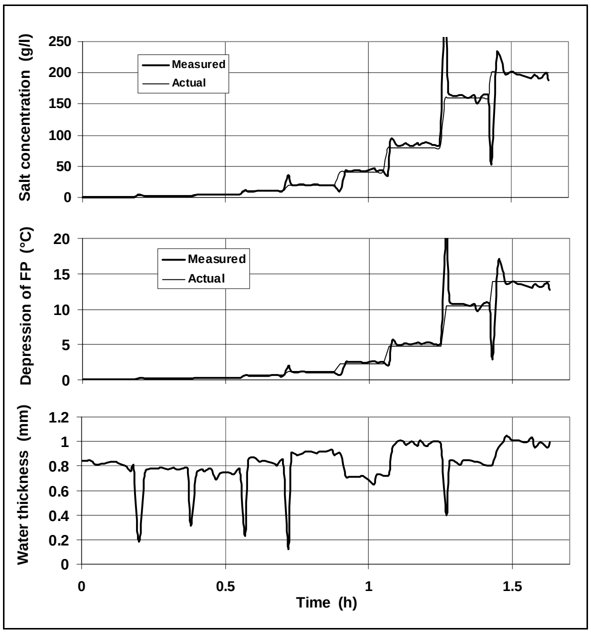

Figure 5. Measured depression of freezing point (DFP) versus actual value as a function of time.

Figure 6 shows the measured depression of freezing point as a function of the actual data. The values at 0°C are the same as in Figure 5. Two measurements were taken at room temperature to reveal repeatability. We may conclude that an accuracy of better than 10% can be achieved for measuring depression of freezing point at less than 8°C and an accuracy of better than 15% can be achieved at higher salt concentrations.

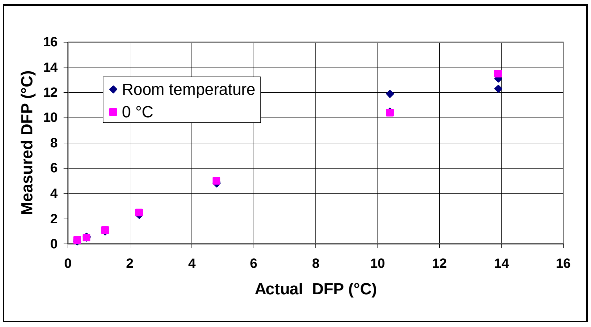

Figure 6. Measured depression of freezing point (DFP) versus actual value.

Obviously, the accuracy of DFP measurement that can be attained in the laboratory cannot be attained in the road environment. Passing traffic will throw the measurements off to some degree. Also, salt is not spread with perfect evenness across the road. This will lead to ambiguity in the measurement results, especially immediately after spreading, when compared to average measurements across a larger area of road surface. Nevertheless, local measurement is required and must be as accurate as possible for assessing the potential slipperiness of a given section of road.

3. FIELD TESTS ON THE ROAD SURFACE

3.1 Testing Principle

Laboratory tests can be used to validate sensor performance under controlled conditions, but field tests must be conducted in real operational conditions. Several field tests were conducted with the DRS511 in Finland and in Ohio, the USA, over several winter periods in 1998-2001.

The objective was to compare road conditions (dry, moist, wet, icy, snowy, frosty) as observed by humans against the information provided by the DRS511 sensor connected to an automated road weather station (Vaisala ROSA station). To ensure that the results were objective, the human observations were made in complete isolation from the DRS511 tests.

3.2 Field Tests in Finland

The Finnish field tests were conducted at the Utti road weather station in south-eastern Finland during periods of the winters of 1998-99, 1999-2000 and 2000-01. The road weather station was located beside a two-lane main highway carrying an average of 8,700 vehicles per day. The road is classified as ”first class” in winter maintenance terms: it is salted and kept clear of snow and ice. The test site was therefore a typical Finnish road weather station site, chosen for its demanding winter weather characteristics. It was to yield a wide range of pavement condition states.

To ensure the objectiveness of the human observations, the observers were drawn from the staff of the Finnish National Road Administration. They made a total of 817 independent human observations on pavement conditions during the three winter weather periods beginning in October and ending in April. Observations were collected at different times of the day, almost every day.

The human observations were made by driving past the road weather station in order to represent, as closely as possible, the typical road user's impression of road conditions. The disadvantage of this method lies in the lack of close observation of the road surface condition, which led to a greater error rate in the human observations at certain times. Since pavement conditions can vary across the road, a more detailed human observation of the different parts of the road (wheel track, center of the lane) and observations from the exact sensor locations would have had to be made at the same time for complete coverage, Haavisto (2000). This was beyond the scope of the Utti field test. Figure 8 is a photograph of the test road section, showing a situation where the wheel tracks are clear of snow but the center of the lane is covered with packed snow. In a situation like this it is impossible to be certain that the "drive-by" human observer and the sensor are comparing the same part of the road.

Figure 7. Utti test location in south-eastern Finland; pavement sensor locations are shown with arrows

Figure 8. Photograph of the test location showing wide variation in pavement conditions across the road

The road conditions as observed by humans were classified according to six road surface states: DRY, MOIST, WET, ICY, SNOWY or FROSTY. This classification gave sufficiently detailed information on the condition of the road surface for the purposes of this test. The road weather station reported eight road surface states: DRY, MOIST, MOIST & CHEMICAL, WET, WET & CHEMICAL, ICY, SNOWY or FROSTY. If we exclude the chemical component, this classification is the same as that used by the human observers. The "chemical states" MOIST & CHEMICAL and WET & CHEMICAL simply indicated that de-icing chemical was present on the road. For the sake of comparison, these categories were treated as MOIST and WET respectively.

At the conclusion of each winter testing period, the data generated by the human observations were compared against the data generated by the road weather station. The results are shown in the comparison matrices of Figures 9, 10 and 11. In the comparison process, the results were grouped into three categories: a "perfect match" means that the human observer and road weather station specified the same road surface condition. If the human observer and road weather station observed almost the same surface condition (e.g. human observation= moist, RWS observation=wet or human observation=snowy and RWS observation=icy), the result was placed in the category of "no significant difference". The last category, "significant difference", is self-explanatory.

The comparison matrices show a consistent match rate of 86% for the Utti test site during all three years. This result can be regarded as very good, bearing in mind that the observation method and the variation of the pavement conditions across the road made it impossible to obtain a perfect match of the results.

Human observations	Road Condition by DRS511 Sensor: DRY	MOIST (&CHEM)	WET (&CHEM)	ICY	SNOWY	FROSTY
DRY	**93**	75	5	15	2	0
MOIST	13	**109**	23	15	0	0
WET	7	28	**79**	2	0	0
ICY	14	8	1	**24**	1	0
SNOWY	6	2	1	33	**22**	0
FROSTY	1	1	0	4	0	**0**

= Perfect match
= No significant difference
= Significant difference

Match Rate Total 86.3%
(percentage of cases in which the measured pavement condition does not significantly differ from the human observation)

Figure 9. Pavement condition field test results, Finnish test site in Utti, winter period 1998-99

Human observations	Road Condition by DRS511 Sensor: DRY	MOIST (&CHEM)	WET (&CHEM)	ICY	SNOWY	FROSTY
DRY	**87**	46	0	1	0	0
MOIST	1	**121**	8	11	0	0
WET	1	37	**65**	6	0	0
ICY	5	22	0	**37**	0	0
SNOWY	2	15	1	46	**7**	0
FROSTY	1	9	0	7	0	**0**

= Perfect match
= No significant difference
= Significant difference

Match Rate Total 86.2%
(percentage of cases in which the measured pavement condition does not significantly differ from the human observation)

Figure 10. Pavement condition field test results, Finnish test site in Utti, winter period 1999-2000

Human observations	Road Condition by DRS511 Sensor: DRY	MOIST (&CHEM)	WET (&CHEM)	ICY	SNOWY	FROSTY
DRY	**103**	20	0	7	0	0
MOIST	10	**92**	10	23	0	0
WET	5	77	**59**	2	0	0
ICY	8	3	1	**35**	0	0
SNOWY	8	5	4	19	**9**	0
FROSTY	3	2	0	9	0	**0**

= Perfect match
= No significant difference
= Significant difference

Match Rate Total 86.2%
(percentage of cases in which the measured pavement condition does not significantly differ from the human observation)

Figure 11. Pavement condition field test results, Finnish test site in Utti, winter period 2000-2001

3.3 Field Tests in Columbus, Ohio

The methodology of the field test carried out in Columbus, Ohio was identical to that of the Utti field test with one major difference. This difference was that the pavement condition was checked by human observers who walked over to the sensor location, i.e. there were no ”drive-by” human observations. This allowed more accurate observations to be made on the exact surface condition at the sensor location. In many cases the sensor condition was photographed to allow further study of the pavement condition. Figure 12 is a photograph of the Ohio test road section on a winter day. Figures 13, 14 and 15 show the DRS511 and different pavement conditions.

Figure 12. Ohio road test section

The Columbus field test was carried out over the winter period December to March of 1999-2000. The Columbus field test used two DRS511 sensors connected to an automated road weather station (Vaisala ROSA station). In this case, employees of Vaisala Inc., Columbus, Ohio, served as the human observers.

As in the Utti field tests, the resulting data set was analyzed at the conclusion of the test period. The data set contained 248 human observations for each of the two DRS511 sensors used, for a total of 496 human observations.

The results are shown in comparison matrices that are similiar to the Utti comparison matrices. See Figures 16 and 17. The results of the analysis show a very high match rate between the human observations and DRS511 observations from the ROSA road weather station. The match rate is 97% for both DRS511 sensors – more than 10% higher than in the Utti field test. The explanation for this may lie in the difference between the Utti ”drive-by” method of human observation and the Columbus ”on-the-spot” method. The Columbus method allowed the human observers to directly characterize the road surface state in the sensor’s precise location. Naturally the differences in the road microclimate and differences in the road maintenance practices can cause some difference in the results as well.

Figure 13. Dry road and DRS511

Figure 14. Ice on the DRS511

Figure 15. Snow on the DRS511

Human observations	Road Condition by DRS511 Sensor					
	DRY	MOIST (&CHEM)	WET (&CHEM)	ICY	SNOWY	FROSTY
DRY	123	0	0	0	0	0
MOIST	0	73	0	1	0	0
WET	0	2	19	0	0	0
ICY	0	1	0	5	0	0
SNOWY	1	0	4	2	17	0
FROSTY	0	0	0	0	0	0

= Perfect match
= No significant difference
= Significant difference

Match Rate Total **97.2%**
(percentage of cases in which the measured pavement condition does not significally differ from the human observation)

Figure 16. Road surface condition field test results, Columbus, Ohio, sensor 1, winter period 1999-2000

Human observations	Road Condition by DRS511 Sensor					
	DRY	MOIST (&CHEM)	WET (&CHEM)	ICY	SNOWY	FROSTY
DRY	121	2	1	1	0	0
MOIST	0	72	1	0	0	0
WET	0	8	16	0	0	0
ICY	0	0	0	6	0	0
SNOWY	0	0	4	2	13	0
FROSTY	0	1	0	0	0	0

= Perfect match
= No significant difference
= Significant difference

Match Rate Total **97.2%**
(percentage of cases in which the measured pavement condition does not significally differ from the human observation)

Figure 17. Road surface condition field test results, Columbus, Ohio, sensor 2, winter period 1999-2000

4. SUMMARY AND CONCLUSION

This paper has presented the Vaisala DRS511 Pavement Sensor and the methodology and results of laboratory and field tests in which the DRS511's performance was analyzed. The DRS511 features unique fiber optic measurement of water/ice layer thickness and presence of snow.

In the laboratory, the DRS511's ability to measure water layer thickness was tested along with the accuracy of the salt concentration calculation and calculation of depression of freezing point. It was found that an accuracy of ±0.1 mm was achieved in the water thickness range of 0.0 to 1.0 mm and an accuracy of about ±1°C for salt concentration was achieved when expressed in terms of depression of freezing point.

The detection accuracy of the DRS511 sensor's ability to measure pavement condition was field-tested with the DRS511 sensor connected to a Vaisala ROSA road weather station. In the field test the pavement condition reported by a human observer was compared with the result obtained from the DRS511 sensor (attached to the ROSA road weather station). To ensure objectiveness, the human observer did not know the result from the DRS511 sensor. The field tests were performed in a test site in south-eastern Finland and in Columbus, Ohio, the USA. The test period in Finland reported in this paper lasted three winters from 1998 to 2001. The test period in Columbus, Ohio was one winter period: 1999-2000.

The field test results show an 86% to 97% match rate between the human observations and the results from the automated weather station equipped with the DRS511. The lower match rate (86%) was obtained from the test in south-eastern Finland; the Ohio test results show a higher match rate of 97%. The main reason for this difference is most likely the difference in the test set-ups. At the Finnish test site, the human observations were made while the observers drove past the site; in the Ohio test, the human observers walked up to the sensor location. The latter method produced more accurate human observations.

The results of the field tests can be summarized with the statement that the DRS511 pavement sensor is capable of detecting, with excellent accuracy, the pavement surface conditions that most affect driver safety and which therefore are of the most interest to road maintenance supervisors.

Moreover, the analysis of the laboratory and field test results suggest that the DRS511 sensor measures pavement conditions with sufficient reliability to be used with traffic control technologies such as variable message signs, bridge sprayers and automatic, weather-controlled speed limit systems.

More information can be found at http://www.vaisala.com.

5. ACKNOWLEDGEMENTS

The authors wish to thank Yrjö Pilli-Sihvola and Kimmo Toivonen of the Finnish National Road Administration for their help in arranging and conducting the Finnish field-tests. Similarly, we wish to thank Jake Trimpey and Roger Hammill of Vaisala Inc., Columbus, Ohio, for their work on the Columbus field trial. Thanks must also be extended to Markus Turunen and Pauli Nylander of Vaisala Oyj for their work in developing the DRS511 sensor and the Vaisala ROSA Road Weather Station.

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