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Remote Sensing of Weather and Road Surface Conditions: Is Technology Mature for Reliable ITS Applications?

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ABSTRACT

Advances in road weather sensing technologies have made non-invasive road weather sensors a valuable component in many Intelligent Transportation Systems (ITS) applications. The current study presents an investigation into the reliability of using one of the aforementioned sensors for a proposed weather-responsive variable speed limit system. The Vaisala surface state and temperature sensors (DSC-111 and DST-111) were selected for the proposed application. The sensors' ability to provide accurate and reliable data was tested under various conditions in a controlled laboratory environment. Specifically, four outputs of interest from the sensors were tested in this investigation; surface state, snow and ice depth, water depth and grip level. Testing results showed that the sensors determined the surface state (dry, moist, wet, snowy and icy) accurately and reliably. The sensor's snow depth readings were found to be inaccurate, while the sensor's ice depth measurements were found to be relatively close to the actual depths. In regards to water depth, only a limited number of readings were close to the actual depths while other readings were highly inaccurate. In an effort to test the potential of the sensor in providing reliable inputs to the proposed ITS application, a calibration was conducted for the sensor water depth measurements using various water depths and sensor installation angles. Calibration results showed that the water depth could be accurately estimated using the calibrated sensor measurements regardless of water depth or sensor installation angle. Sensor estimates of grip level were found highly correlated to the coefficient of static friction for the conditions considered in this study.

Keywords: weather sensor, snow, friction, calibration, ITS

INTRODUCTION

Weather conditions have significant impact on the safety and operations of the highway transportation system. Extreme and inclement weather is a common occurrence during the winter season in many areas particularly those located in Northern United States and Alaska. Advanced sensor technologies capable of monitoring roadway and environmental conditions have found important applications in practice and they constitute a major component of weather-adaptive safety and control applications. Highway agencies in areas more susceptible to extreme weather conditions should take advantage of those technologies and other ITS technologies to improve the safety and efficiency of the transportation system.

In practice, road weather sensors are often used as part of Road Weather Information System (RWIS) stations, and to a lesser extent, as components of the recent weather-responsive advanced transportation applications. Examples of latter applications are the safety warning systems for inclement weather conditions (ice, wind, fog, etc.) using Dynamic Message Signs (DMS) and the weather-responsive variable speed limit (VSL) systems which adjust the posted speed limit under different weather and road surface conditions. (1, 2) With the advances in sensor, communications and control technologies, these and similar applications are expected to increase in the foreseeable future.

Sensors that focus on the condition of the roadway pavement are generally of two types: in-pavement and non-invasive. In-pavement sensors are puck shaped sensors that are set in the roadway and can measure important parameters such as pavement temperature, precipitation occurrence, precipitation type, and depth of precipitation. Non-invasive sensors use infrared spectroscopy principles to measure road surface conditions from above the roadway. Non-invasive sensors can measure all the parameters measured by the in-pavement sensors besides the level of grip between the tire and pavement. Both types of road weather sensors are used in conjunction with the RWIS applications.

NON-INVASIVE SENSORS: BACKGROUND

The non-invasive road weather sensors employ relatively new technology that is less proven than the older, more common in-pavement road weather sensors. In the course of this research, only a few manufacturers were identified as producers of non-invasive road weather sensors with capabilities that meet the requirements of the proposed application. However, other than manufacturer's literature and website information, no independent studies have been identified to test the capabilities of the sensors and consequently the reliability of using sensor outputs in automated ITS applications. The only exception to the previous statement was the Vaisala weather sensors that were selected in this research project for the VSL application. A few studies were conducted to test the sensors that are described next in this section.

For road weather conditions, Vaisala offers two weather sensors, the remote road surface state sensor (DSC-111) and the remote road surface temperature sensor (DST-111). The two sensors that are used in combination have been in the market for the last few years and were tested in a few studies. Two studies were conducted by Aurora, which is an international partnership of public agencies performing joint research, evaluation, and deployment initiatives related to road weather information systems (RWIS) (<http://www.aurora-program.org/index.cfm>). These two studies attempted to examine the Vaisala sensors by installing the sensors in the field and comparing sensor outputs with data gathered from in situ sensors to determine if the data were accurate.

The first study was conducted east of Ottawa in Ontario, Canada (3). This study found that the Vaisala sensors were reliable and accurate in determining road surface state and that there were systematic differences in temperature measurements between the Vaisala sensor and the in-situ sensor used in the study. Further, the grip levels reported by the Vaisala sensor did not correlate well with the friction coefficients measured by a friction meter at the same location and time interval, especially under conditions of low friction. The study concluded that the DSC-111 cannot be used as a reliable replacement of friction measuring equipment.

The second Aurora study was conducted in North Dakota (4) adjacent to Interstate 29 south of Grand Forks. The study found that the Vaisala sensor suite produced results, with respect to pavement temperature, that were comparable to current in situ technologies and that fog could impact the Vaisala sensor temperature readings. Also, the sensor was reportedly able to determine the pavement conditions reasonably well compared to camera images of the road surface.

A third field study of the sensor was performed in Sweden (5). The testing found the sensor to be accurate at determining the surface condition of the pavement. Friction estimates reported by the sensor were also found to be reasonable when compared to the wheel type friction tester used for comparison. The snow depth measurements were found to be inaccurate. Overall conclusions stated the sensor showed promise for further testing and use.

OBJECTIVE

The objective of this study is to test the ability of the Vaisala non-invasive weather sensors DSC-111 and DST-111 in measuring weather parameters that are of interest to the proposed VSL system. The tests and validations that were reported in the literature and summarized above are limited in a sense that it either compared the sensor's outputs to their counterparts from other pavement weather sensor technologies or considered only limited weather parameters in their testing. The current study, in return examines four important weather parameters namely: pavement surface state, water depth, ice and snow depth and the grip level. The study tests the accuracy of the sensor outputs relevant to the actual values measured in a controlled laboratory environment. This testing is expected to provide a more accurate assessment of the capabilities and limitations of the Vaisala weather sensors for the proposed VSL or other similar ITS applications.

APPLICATION AND SENSOR OVERVIEW

This investigation was done in the course of developing a weather-responsive variable speed limit system to be installed at the ramps of the US-26 / Oregon 217 interchange in the state of Oregon. Commercially available weather sensors were screened and examined for satisfying the general requirements of the proposed application using published literature. Upon careful consideration, the research team selected two Vaisala non-invasive weather sensors, the DST-111 temperature sensor and the DSC-111 road condition sensor. The DST-111 measures infrared radiation to determine road surface temperatures while the DSC-111 uses spectroscopic methods to determine roadway conditions and water film depths. The DSC-111 and DST-111 are typically used in tandem to ensure the best possible measurements. The sensors are typically mounted on a pole at a measuring distance up to 15 meters away from the road surface.

TESTING METHODS AND RESULTS

The sensor testing in this study involved four important road weather parameters that are estimated by the weather sensors. These include surface state, tire-pavement grip level, snow and ice depth and water depth. The following sections briefly describe each of these individual tests summarizing methodology, experimental design and the most important results and findings.

SURFACE STATE DETERMINATION

The sensor's ability to determine the surface state of the roadway was tested. The manufacturer reports that the sensor can determine the road condition as dry, moist, wet, frosty, snowy, icy, or slushy.

Testing Method and Experimental Design

The surface state determination testing was performed at the Montana State University (MSU) Subzero Science and Engineering Research Facility in Bozeman, Montana. This research facility has a number of large, walk-in environmental chambers (cold labs) that can be programmed to precise temperatures for testing. This allowed for sensor tests to occur under different temperature conditions in a fully controlled environment.

The sensors were secured atop a tripod set up in the cold lab and connected via an RS-232 communications cable to a laptop placed outside the lab. The free data terminal program PuTTY was used to send commands to and receive data from the sensors.

The sensors were positioned so that the measuring distance to the pavement samples was approximately 3 meters and the installation angle was approximately 37 degrees. The sensor installation angle is the angle measured from the horizontal road surface up to the sensor line of sight. This set-up complies with the limits for installation published by the vendor, fits within the cold lab, and ensures that the DSC-111's measurement ellipse was appropriately sized based on the dimensions of the pavement samples. Specifically, the measuring distance of the sensors must be between 2 and 15 meters from the pavement, with an installation angle between 30 and 85 degrees according to the manual. The measurement ellipse is the area on the sample that is measured by the DSC-111, and this ellipse becomes larger as the measurement distance increases. The DSC-111 Aiming Tool Kit was used to position the pavement samples on the floor to ensure they were being accurately measured.

One asphalt sample (9 inches wide, 20 inches long, and 1 inch thick) and one concrete sample (12 inches wide, 16 inches long, and 2 inches thick) were used to simulate roadway surfaces for testing. These samples were chosen from available materials with appropriate dimensions for testing. A silicon barrier was added near the outside edge of each sample to allow precipitation to pond on the surface of the samples.

The laboratory testing simulated a variety of surface conditions including dry, moist, wet, covered with loose snow, covered with compacted snow, and ice with various depths. The depths were chosen based on the reported capabilities of the DSC-111. As suggested in the DSC-111 manual, the sensor was calibrated for the dry condition for each sample before changing conditions. For each condition and corresponding pavement sample, the DSC-111 output was monitored until the readings stabilized, at which time the sensor readings were recorded.

The moist condition was considered to exist when the surface is visibly damp but no standing water is present. Water was applied with a trigger type squirt bottle set to spray a mist

of water (not a stream of water). Wet samples with increasing water depth were created by spraying multiple lifts of water and allowing the DSC-111 readings to stabilize between lifts. Snow created by the Subzero Science and Engineering Research Facility was used to simulate loose and compacted snow conditions. As with water, the desired depth of snow was created slowly with multiple lifts, allowing the DSC-111 readings to stabilize between lifts. The snow was compacted manually with a pressure of approximately 200 lbs per square foot. Ice was created using the same technique as the water application but each lift of water was allowed to freeze on the sample.

Results and Analysis

The DSC-111 identified all five surface conditions correctly for both asphalt and concrete samples, as shown in Table 1. Furthermore, for the ice condition, the DSC-111 initially reported water, then slush and then ice as the water froze on the sample.

TABLE 1 Comparison of DSC-111 Reported Surface State to Actual Conditions

Sample	Actual Surface Condition	Temperature (°F)	DSC-111 State
Both	Dry	45	Dry
Both	Dry	15	Dry
Both	Moist	45	Moist
Both	Wet (depth 1)	45	Wet
Both	Wet (depth 2)	45	Wet
Both	Wet (depth 3)	45	Wet
Both	Loose Snow (depth 1)	15	Snowy
Both	Loose Snow (depth 2)	15	Snowy
Both	Compacted Snow	15	Snowy
Both	Ice	15	Icy

As illustrated in Table 1, the sensor accurately classified the surface state of the samples as dry, moist, wet, snowy or icy for all conditions tested on both asphalt and concrete samples. There were twenty total occurrences of these different conditions during testing and the sensor accurately reported the state of the simulated road surface all twenty times.

TIRE-PAVEMENT GRIP LEVEL

The sensor outputs a grip number based on the road weather conditions it measures. The grip number reported by the DSC-111 is a relative measure of expected friction between the tire and road surface and varies between 0 and 1.

Measuring the friction experienced by a vehicle is difficult and is dependent on the temperature of the surfaces involved. Many devices aim to express a relative grip level between the vehicle's tires and the road surface, but any metric developed is unique to the measurement device used. For this reason and being limited to the laboratory setting a coefficient of static friction (CSF) tester was used for comparison to the sensor's grip number. The CSF was measured using a steel tester weighing 9.23 pounds, with a 4 inch square of smooth neoprene rubber bottom (durometer rating of 30A). A spring scale was used to measure the side force needed to overcome static friction.

As the DSC-111 grip number is intended to represent the skid resistance qualities of pavement surface, it is logical expected to closely correlate to the friction measured by other vehicle-roadway friction measurement devices. The CSF is a physical friction measurement based on the principle that “the friction coefficient is a measure of the resistive forces of movement between two opposing object surfaces” (6). The CSF tester measures the horizontal force needed to overcome the resistive horizontal component of the normal force to initiate movement. While these two metrics (grip number and CFS) may not be expressing the exact same characteristic, they do both attempt to describe the grip between the tire and pavement and were therefore compared with the understanding that the absolute scales used for each measure are not necessarily equivalent. The DSC-111 grip number has an absolute range of 0 to 1, with 0 being very slick and 1 being high friction. The CSF by definition does have a lower limit of 0 but does not have an upper limit of 1, and often when a rubber surface is involved the CSF may become larger than 1. However, it is reasonable to believe that the two measures should be highly correlated, as both are indicators of the surface friction, and thus skid resistance properties. Considering these factors, and the sensor’s potential use for road weather conditions, this testing focused on examining how consistent and sensible the change in the grip number relative to that in the CSF when tested under various pavement states and conditions.

Testing Method and Experimental Design

The tire-pavement grip level testing was performed at the same location using the same samples and precipitation preparation as described for the surface state determination testing. Again the sensor was calibrated for the dry condition for each sample before changing conditions. For each condition and corresponding pavement sample, the DSC-111 output was monitored until the readings stabilized, at which time the sensor readings were recorded. Six CSF measurements were taken on each sample for each condition. This number of CSF measurements was the highest that could physically fit on the samples without overlapping test areas.

Results and Analysis

The six CSF measurements were averaged for comparison to the DSC-111 grip numbers. The changes in friction are then shown as percent reductions from the dry condition (at the relevant temperature), with friction of dry pavement being equal to 100%. Figure 1 shows the results for asphalt. Error bars showing one standard deviation above and below are presented for each CSF value.

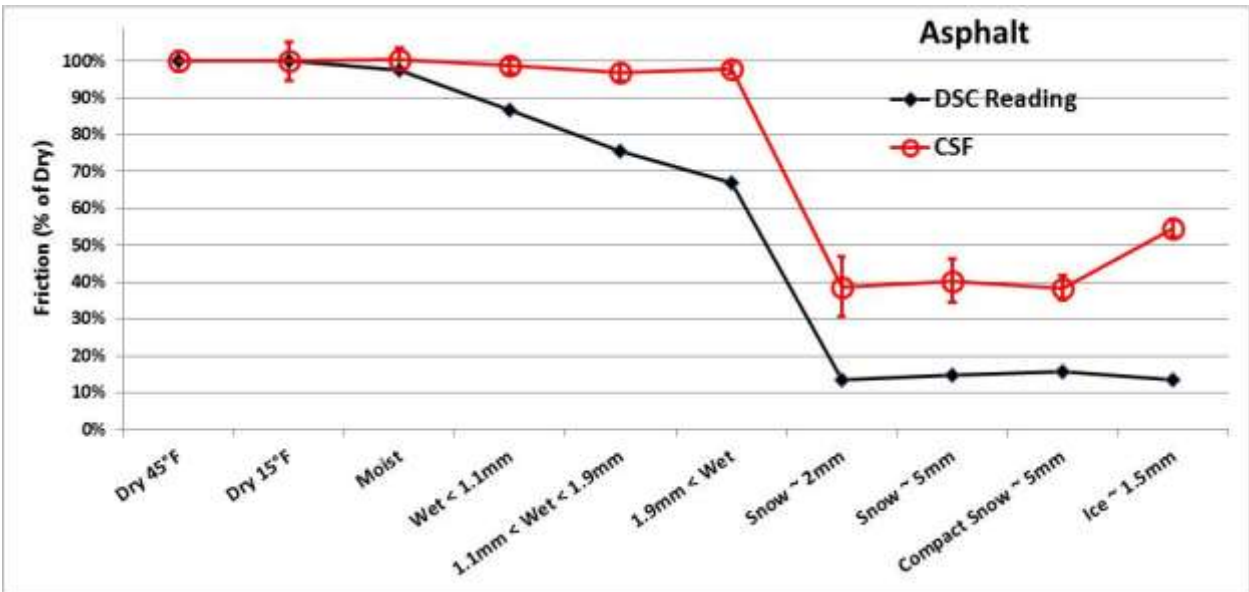


FIGURE 1 CSF and Grip Measurements on Asphalt

The CSF measurements show almost no reduction from dry to wet asphalt while the DSC-111 sensor estimates reductions in grip level when the pavement becomes wet. This may be because the CSF tester displaces almost all of the water from the smooth asphalt surface and the resulting CSF measurement is being performed with very little water remaining between the rubber and asphalt, a situation that highly resembles the contact between the tire and pavement in reality. Significant reductions in friction / grip are observed with snowy and icy asphalt for both CSF and DSC-111 readings. Overall, the water, snow and ice caused more profound reductions in the DSC-111 grip level when compared with the CSF. Figure 2 shows the CSF and grip level test results for concrete.

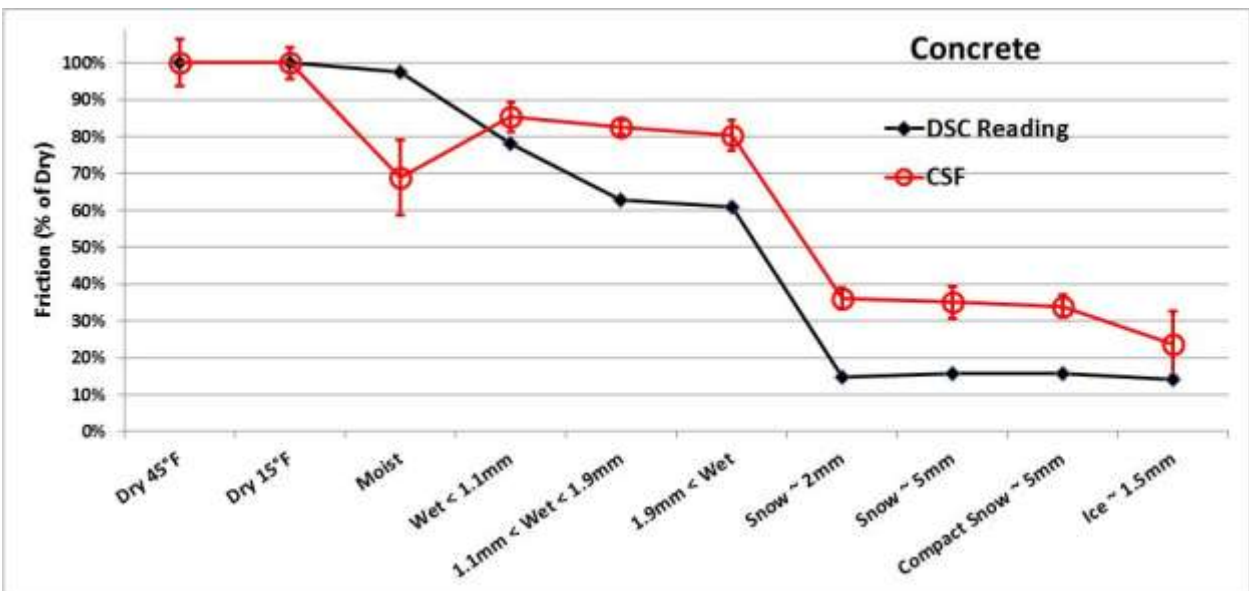


FIGURE 2 CSF and Grip Measurements on Concrete

CSF reductions for wet concrete correlate somewhat well with DSC grip reductions. The moist concrete CSF reduction is more drastic than the DSC-111 grip reduction. Reasons for this discrepancy were not obvious and which value is most representative of actual surface conditions is unknown. The fact that all three wet CSF measurements for concrete were considerably higher than the moist CSF for concrete is curious and may be justification for concluding that the moist CSF difference was due to some anomaly in the experiment and not representative of actual surface conditions. Significant reductions in friction / grip are observed with snowy and icy concrete for both the CSF and DSC-111 readings. Again, with the exception of moist state, the water, snow and ice caused more profound reductions in the DSC-111 grip level readings when compared with the CSF.

Published values were available from past research for asphalt pavements tested under similar conditions as those tested during this investigation. Two studies, one sponsored by the Swedish National Road Administration (7) and one published in the Journal of Cold Regions Engineering (8), were found to have used other friction measurement devices (Saab Friction Tester and a Portable Friction Tester that both utilize a slipping wheel) on many similar pavement conditions. Another study performed for the Swedish Transport Authority (5) provided field testing results of the DSC-111 grip level measurements. Figure 3 shows the CSF and grip readings from the current study along with the results of the three aforementioned studies all expressed as percentage of the dry asphalt values. Three trends can be discerned in Figure 3. First, the DSC-111 grip level readings from the current and Swedish studies generally showed higher reductions under wet, snowy and icy conditions compared with the friction coefficients. Second, The DSC-111 readings from the current study are relatively in agreement with those reported in the Swedish study. Third, the coefficient of kinetic friction showed more reductions in value compared with the CSF particularly under icy and snowy conditions.

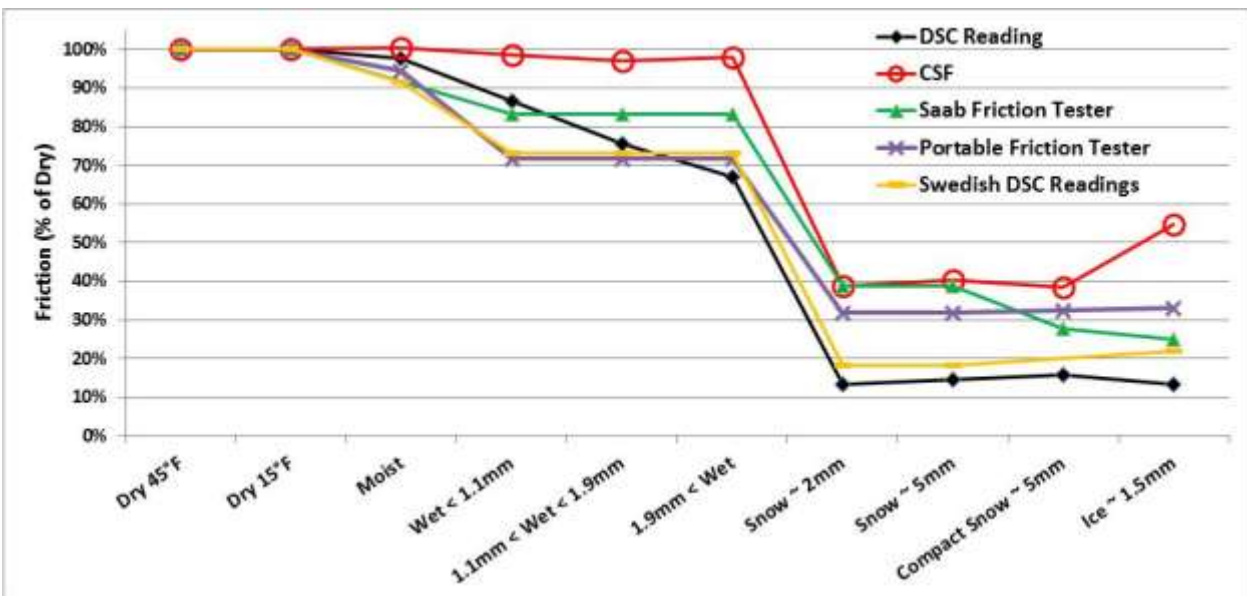


FIGURE 3: CSF, Grip Measurements, and Published Values on Asphalt

The coefficient of correlation (COC) was found for the CSF measurements and grip number. The COC for the concrete surface was found to be 0.924 and the COC for asphalt was found to be 0.959. These values indicate a very high correlation between the CSF and DSC-111 grip level

A student's t-test was completed to determine if a significant relationship exists between CSF and grip number. For asphalt the t stat was found to be 24.6 and for concrete 17.5. This is done with a sample size of 60 measurements which results in a probability of over 99% that the two friction metrics are related for both asphalt and concrete samples.

SNOW AND ICE DEPTH

The sensor's ability to measure snow and ice depths was also tested. The sensor reportedly measures ice depths, and snow amount as equivalent water content (wc) depth.

Testing Method and Experimental Design

The snow and ice depth testing was performed at the same location using the same samples and precipitation preparation as described for the surface state determination and friction testing. Again the sensor was calibrated for the dry condition for each sample before changing conditions. For each condition and corresponding pavement sample, the DSC-111 output was monitored until the readings stabilized, at which time the sensor readings were recorded. Snow depths were physically measured using a transparent ruler. Ice depths were physically measured using digital calipers. Snow density was measured using a small cylindrical dish with known volume and a weight scale.

Results and Analysis

The physical snow and ice depth measurements were compared to the sensor measurements for all conditions. The sensor reports snow in water content (wc) depth. The depth and density measurements of the snow were used to calculate equivalent water content depth, which could be directly compared to the DSC-111 readings. The comparison between actual depth and DSC-111 reported depth is shown in Table 2.

TABLE 2 Comparison of Sensor Snow and Ice Depths to Physical Measurements

Sample	Actual Surface Condition	Measured Depth (mm)	DSC-111 State	DSC-111 Depth (mm)
Asphalt	Dry	0.0	Dry	0.00
Asphalt	Loose Snow	2 (snow) 0.37 (wc)	Snowy	N/A (snow) 1.01 (wc)
Asphalt	Loose Snow	5 (snow) 0.93 (wc)	Snowy	N/A (snow) 1.26 (wc)
Asphalt	Compacted Snow	5 (snow, compacted) 2.16 (wc)	Snowy	N/A (snow) 1.21 (wc)
Asphalt	Ice	1.4	Icy	1.54
Concrete	Dry	0.0	Dry	0.00
Concrete	Loose Snow	2 (snow) 0.37 (wc)	Snowy	N/A (snow) 0.78 (wc)
Concrete	Loose Snow	5 (snow) 0.93 (wc)	Snowy	N/A (snow) 0.82 (wc)
Concrete	Compacted Snow	6 (snow, compacted) 3.17 (wc)	Snowy	N/A (snow) 0.79 (wc)
Concrete	Ice	1.5	Icy	1.40

The snow depths reported by the DSC-111 do not appear to reasonably correlate to the physical measurements. Specifically, the depths reported by the sensor were overestimated for loose snow on asphalt and when the concrete was covered with only two inches of loose snow. On the other hand, the sensor reported snow depths were severely underestimated for compacted snow on asphalt and concrete and was slightly less than the actual depth when the concrete was covered by five inches of loose snow. Evidently, the sensor readings varied in a relatively small range and were not highly sensitive to the actual snow water content measurements especially for compacted snow. In regards to ice depth, the sensor reported depths for the asphalt and concrete samples were relatively close to the actual depths.

WATER DEPTH

The depth of water output from the sensor was also tested. Initially the installation angle of 37 degrees (the same as was tested for ice and snow) was tested at room temperature. The manufacturer claimed the sensor is accurate up to 2 mm water depth.

Methods

The water depth sensor testing was performed at the Western Transportation Institute in Bozeman, Montana. The sensors were positioned so that the measuring distance to the sample was approximately 3 meters and the installation angle was 37 degrees. This was done to comply with the limits for installation values published by the vendor, to fit within the available space, and to ensure the DSC-111's measurement ellipse was appropriately sized based on the dimensions of the sample.

A Modified Proctor Test mold base piece was used for ponding water. This sample was chosen because of its shallow cylindrical shape with known dimensions and a flat surface allowing for very accurate and consistent water depth measurements. The water ponding area of the sample was 165 mm in diameter and approximately 3.5 mm deep. Physically measuring very small depths of water present on an asphalt or concrete surface was found to be problematic. By using the ponding area of known dimensions, a volume of water could be measured out and applied to ensure consistent and accurate physical water depths.

The testing simulated a wet surface with water depths ranging from 0 mm to 3 mm. The depths were chosen based on the reported capabilities of the DSC-111. The sample was leveled before each test. As suggested in the DSC-111 manual, the sensor was calibrated for the dry condition before adding water for each set of tests. For each water depth, the DSC-111 output was monitored until the readings stabilized, at which time the sensor readings were recorded and compared to the known depth of water present on the sample. Water was measured and applied using a graduated cylinder and graduated pipette.

Results and Analysis

When the actual depth measurements were compared to the sensor reported water depths, some inaccuracies were observed. Figure 4 shows the actual and sensor reported water depths. This figure shows that the DSC-111 consistently overestimated water depth for all depths above 0.5 mm. The sensor readings for water depths less than 0.5 mm were largely consistent with the actual water depth measurements.

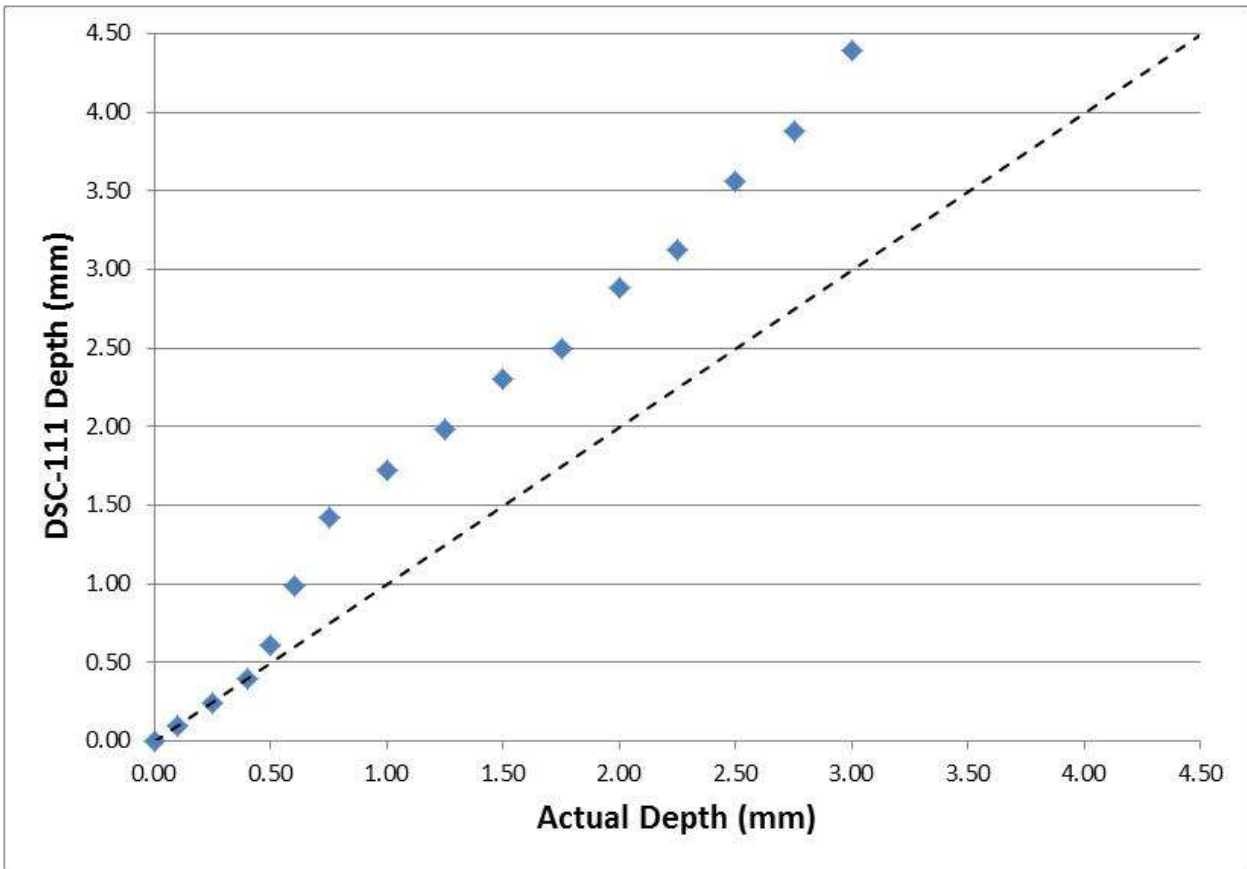


FIGURE 4: Actual Water Depth and Sensor Reported Water Depth for $\alpha = 37$ degrees

IMPROVING SENSOR ACCURACY THROUGH CALIBRATION

For many ITS applications including the proposed VSL application, reliable sensor outputs are essential for the safety and effectiveness of system operations. As demonstrated by the results of the weather sensor testing discussed earlier, some of the sensor outputs are inaccurate and may significantly deviate from the actual values, which could affect the reliability and robustness of the intended applications. It was hypothesized that sensor outputs of various weather parameters could well be affected by installation settings, and therefore, output deviation from the actual values could be minimized should proper calibration be performed for the weather parameter of interest. Given the physical limitations of the cold lab walk-in chambers and the resources available to this research, it was decided to further investigate the above hypothesis by calibrating the sensor outputs for only one parameter, water depth, using the installation angle as the calibration parameter. For reasons related to lab settings, it was not possible to include sensor measuring distance in the calibration investigation.

The calibration effort considered sensor installation angles that are all within the range specified by the manufacturer. Those angles were 50, 60, 70, and 80 degrees. As discussed earlier, the sensor installation angle is the angle measured from the horizontal road surface up to the sensor line of sight. Figure 5 shows the actual water depths and the sensor reported water depths for the previous sensor installation angles before calibration. The results show that the sensor installation angle is an important determinant of the consistency between the sensor

measured and actual water depths. As shown in Figure 5, the sensor produced results with the least deviation from actual values when the angle of installation was 60 degrees. Smaller and larger angles showed greater deviations between sensor output and the actual values. However, even for the 60-degree angle, the sensor underestimated the depth at times and overestimated the depth at other times in a clear trend based on the actual water depth ranges. Similar trends with varying water depths were also exhibited by all other installation angles.

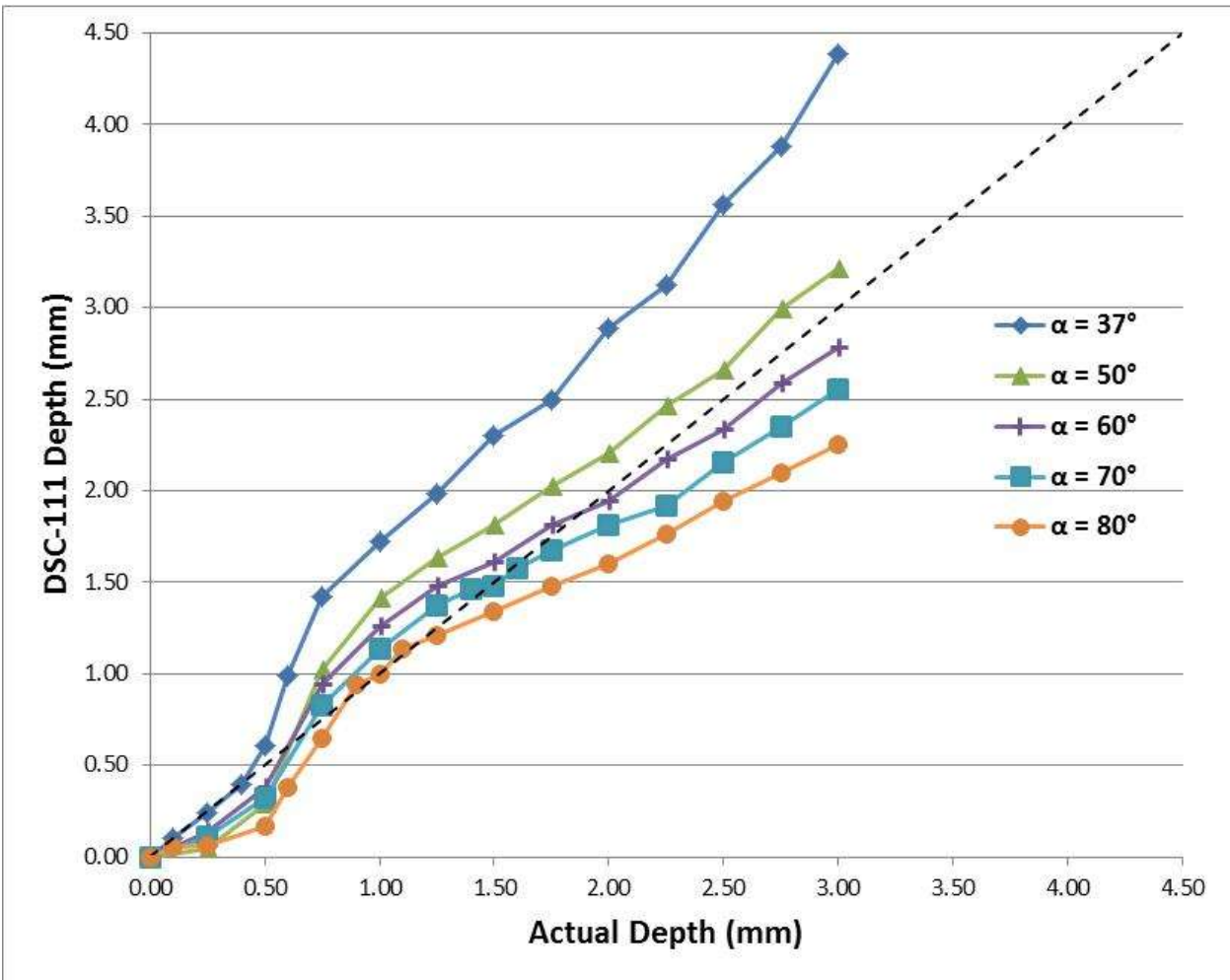


FIGURE 5: Actual Water Depth and Sensor Reported Water Depth for All Initial α

In order to be useful the calibration should be able to take raw sensor readings and correlate those to actual water depths. Using this concept, a calibration table was developed where adjustment factors can be used to estimate the actual water depth from the sensor output water depth. For other installation angles and water depths not shown in Figure 5, the calibration essentially interpolates all possible water depth values for all possible installation angles within the ranges tested. Figure 6 shows all the calibration points for all installation angles from 37 to 80 degrees.

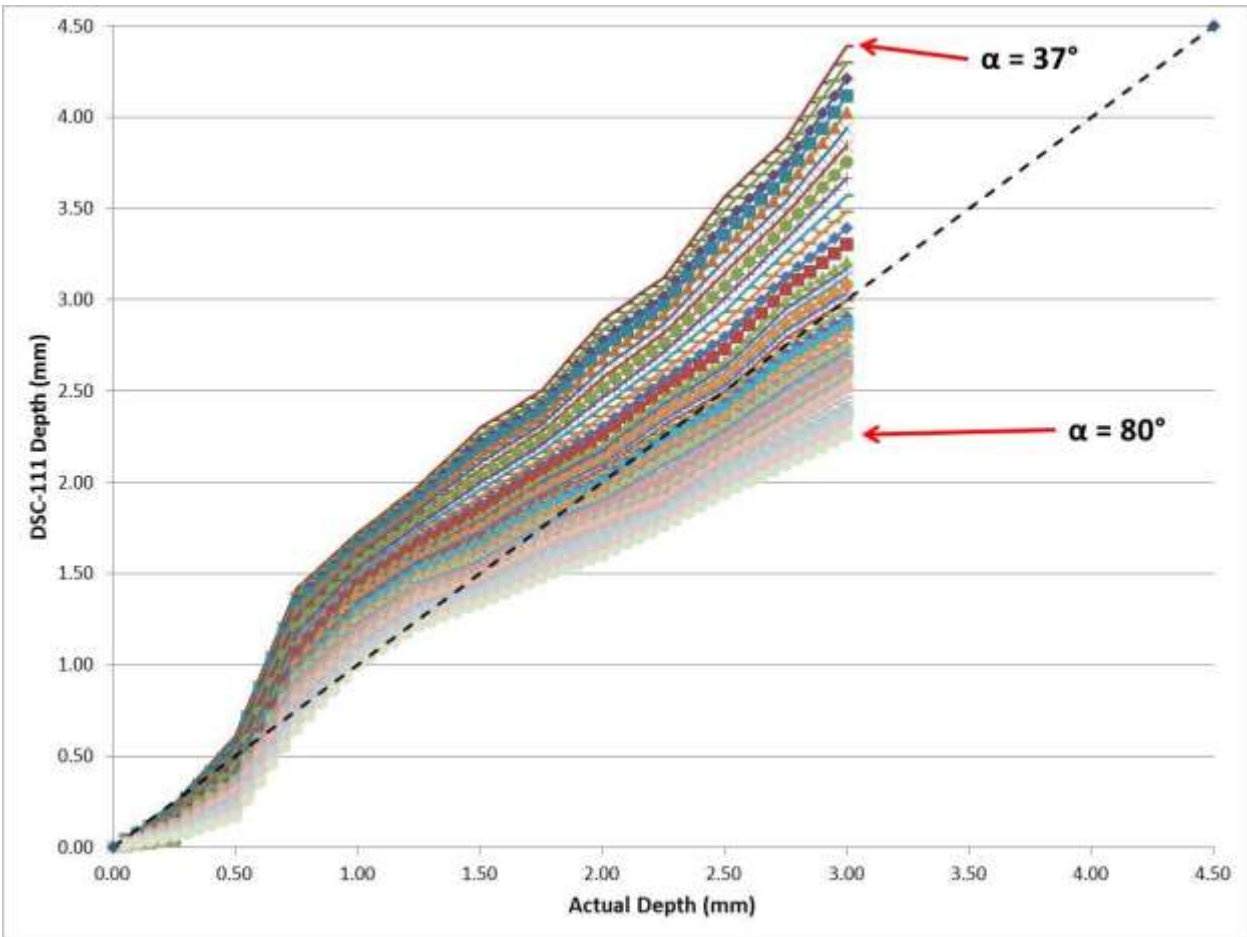


FIGURE 6: Calibration Points for All Angles of Installation and Water Depths

Validation

In order to validate the effectiveness of the calibration discussed earlier, a new set of lab experiments were conducted for use in validating the adjustment factors developed in the calibration process. In the new experiments, installation angles of 45, 55, 65, and 75 were tested using various water depths as was done with the calibration experiments. The raw sensor depths were adjusted using the calibration table factors and results were plotted against the actual values to examine the consistency or discrepancy between the two. The validation results are shown in Figure 7.

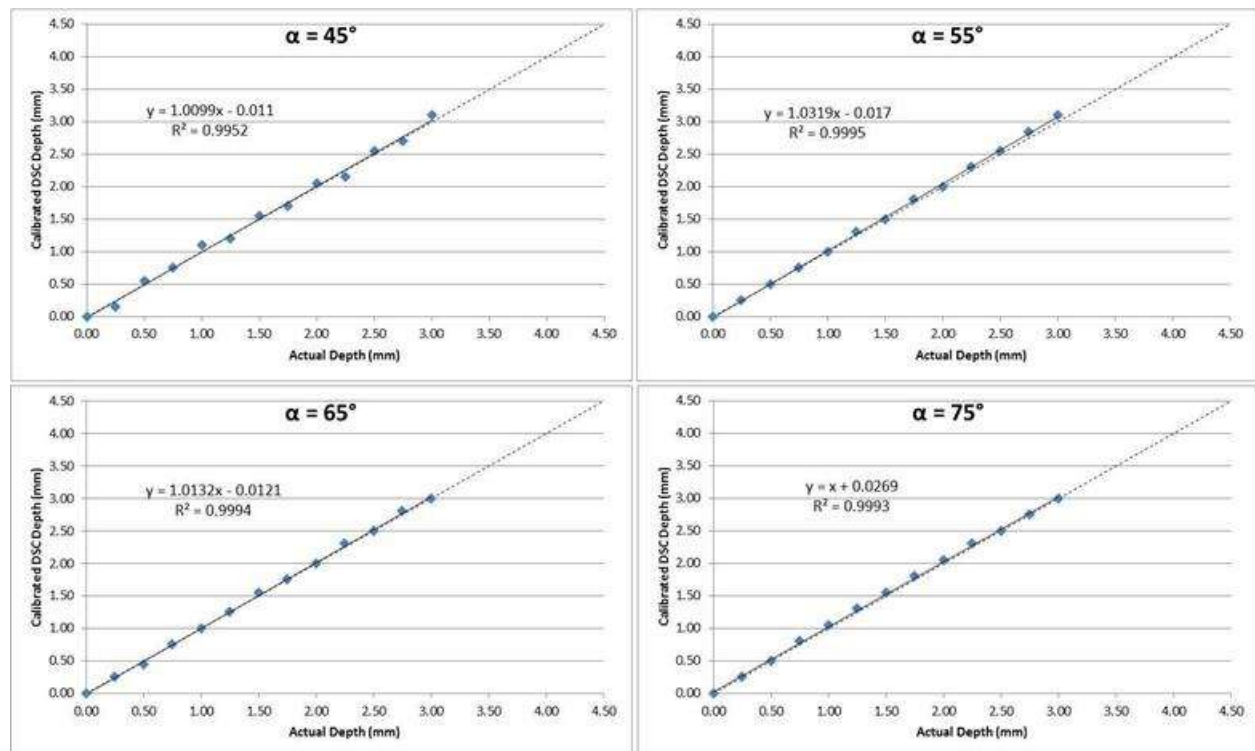


FIGURE 7: Validation Results

It is clear that the calibrated DSC-111 depths are very close to their counterparts of actual depths for the installation angles tested. This is despite the fact that these installation angles were not used in developing the calibration adjustment factors.

Since the calibration accurately produced water depths for angles that are different from those used in calibration, it is logical to expect very high consistency between the calibrated water depths and actual water depths for all angles in the range between 37 and 80 degrees. This exploratory investigation proves that the same calibration process can reasonably be expected to improve the accuracy of weather sensor outputs and thus the reliability of the applications in question.

SUMMARY AND FINDINGS

The current study reports the results of an independent testing of the Vaisala DSC-111 and DST-111 weather sensors for use with a proposed weather-responsive variable speed limit system. Four weather parameters of interest were involved in this testing: pavement surface state, ice and snow depth, water depth and grip level. The major findings of the sensors' testing are:

1. The sensor is accurate and reliable in determining the condition of the road surface. The sensor output matched the actual surface state in all tests performed.
2. While different in scales and numerical values, the sensor produced pavement grip levels for various surface states corresponded reasonably well with the patterns of change of the coefficient of static friction measured in the lab as well as those of the frictional coefficients reported in other studies.

3. Snow depth readings from the sensor were found inaccurate when compared with the actual depths. However, the ability of the sensor to detect the presence of snow may be sufficient for many ITS applications. Ice depths produced by the sensor were found relatively close to the actual depths used in the tests.
4. Water depth measurements produced by the sensor were found inaccurate for depths greater than 0.5 millimeters using the sensor installation set-up for the original tests.
5. The water depth calibration and validation tests suggest that sensor outputs are affected by the sensor installation settings and that proper calibration could significantly improve the accuracy of sensor outputs for use in actual ITS system deployments.

This investigation has shown that non-invasive road weather sensors can provide valuable information about road conditions that could be used in many advanced transportation applications. For those applications to be successful, agencies involved in the use of weather sensors for ITS applications should perform thorough testing of the new products before use in the actual systems. This is particularly important if system decisions using weather data are automated. Equally important, the manufacturers of new sensing technologies should provide adequate guidance and support on sensor's capabilities and limitations, and on how to best calibrate the sensors for the system-specific settings. This is essential for the successful deployment of the new weather-responsive ITS applications.

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