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Help from above

Noninvasive sensors assist with pavement condition

Road weather sensors are widely used in road weather information system (RWIS) applications and, to a lesser extent, as components of recent weather-responsive advanced transportation systems.

Sensors that focus on the condition of the roadway pavement are generally of two types: in-pavement and noninvasive. In-pavement sensors are puck-shaped sensors that are set into the roadway, while noninvasive sensors use infrared spectroscopy principles to measure road-surface conditions from above the roadway. Both types of road weather sensors can measure important parameters such as pavement temperature, precipitation occurrence, precipitation type and depth of precipitation. In practice, the two types of weather sensors are used in conjunction with the RWIS applications.

The noninvasive road weather sensors employ relatively new technology that is less proven than the older, more common in-pavement road weather sensors. Only a few manufacturers provide noninvasive road weather sensors with reported capabilities that allow for their use in advanced ITS applications. The Vaisala remote road surface state sensor (DSC-111) and remote road surface temperature sensor (DST-111) were chosen as candidates for a proposed application investigated by the authors. These sensors are typically used in tandem to ensure the best possible measurements. The sensors were evaluated for their potential use in a weather-responsive variable speed limit (VSL) system. The sensor testing in this study involved four important road weather parameters that are estimated by the

Table 1. Surface State Testing Results

Sample	Actual State	Sensor Reported State	Temp (°F)	Match
Both	Dry	Dry	45	✔
Both	Dry	Dry	15	✔
Both	Moist	Moist	45	✔
Both	Wet (depth 1)	Wet	45	✔
Both	Wet (depth 2)	Wet	45	✔
Both	Wet (depth 3)	Wet	45	✔
Both	Loose Snow (depth 1)	Snowy	15	✔
Both	Loose Snow (depth 2)	Snowy	15	✔
Both	Compacted Snow	Snowy	15	✔
Both	Ice	Icy	15	✔

weather sensors. These include surface state, tire-pavement grip level, snow and ice depth and water depth.

One of seven things

The sensor's ability to determine the surface state of the roadway was tested. The manufacturer reported that the sensor could determine the road condition as dry, moist, wet, frosty, snowy, icy or slushy. The surface state determination testing was performed at the Montana State University (MSU) Subzero Science and Engineering Research Facility in Bozeman, Mont. This research facility has a number of large, walk-in environmental chambers (cold labs) that can be programmed to precise temperatures for testing in a fully controlled environment.

One concrete and one asphalt sample were tested at different temperatures under dry, moist, wet (three depths), loose snow (two depths), compacted snow and ice-covered conditions. The sensors' reported state was then compared with the actual state to determine if the conditions matched. Table 1 shows the results of the surface state testing.

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.

Getting a grip

The sensor outputs a grip number based on the road weather conditions it measures. The grip number reported by the sensor 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. 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 with the sensor's grip number. The CSF was measured using a steel tester weighing 9.23 lb, with a 4-in. square smooth neoprene rubber bottom (durometer rating of 30A). A spring scale was used to measure the side force needed to overcome static friction.

CSF measurements were taken on each sample for each condition and compared with the sensor's reported grip number. Figure 1 shows the CSF measurements (with error bars showing one standard deviation) compared with the DSC sensor's reported grip number for asphalt pavement.

Past research studies were found that used other friction-measurement devices (a Saab Friction Tester and a portable friction tester) on many similar pavement conditions. Both of these friction-measurement devices utilize a slipping wheel rather than measuring static friction. Another study provided field testing results of the DSC-111 grip level measurements. Figure 3 shows the

Figure 1. CSF and grip measurements on asphalt.

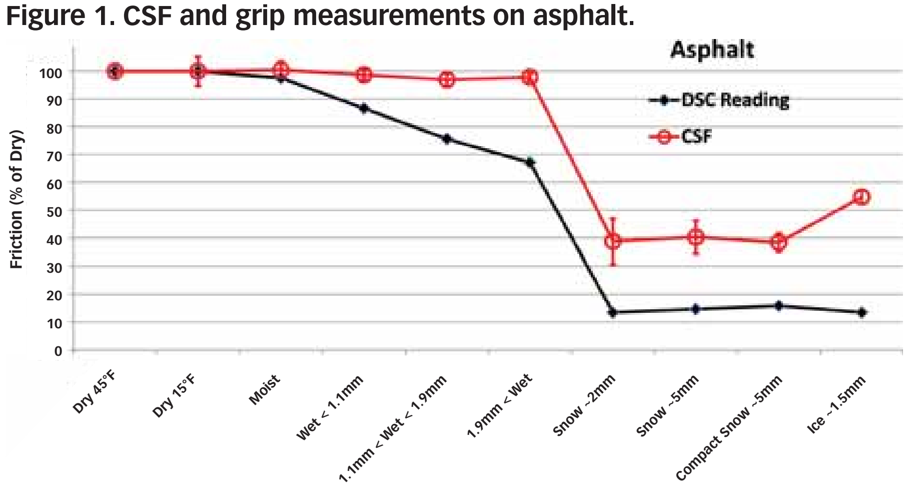
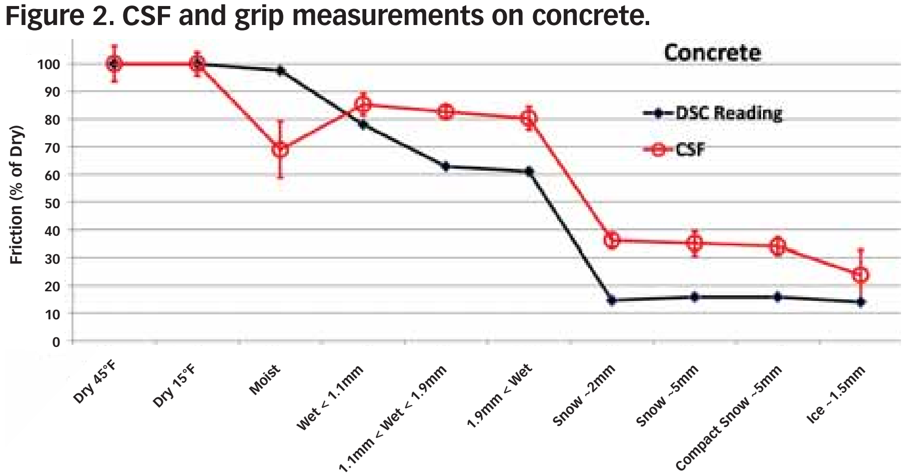


Figure 2. CSF and grip measurements on concrete.



CSF and grip readings from the current study along with the results of the three previously published studies.

In general the patterns of change in diminishing friction values moving from dry to icy conditions are consistent between the CSF measurement and the DSC sensor readings. The CSF is a static friction metric not necessarily the most analogous to actual driving conditions when a vehicle is moving on a roadway.

In the depths of snow, ice

The sensor's ability to measure snow and ice depths also was tested. The manufacturer indicated that the sensor measures ice depths and snow amount as equivalent water content (wc) depth. Snow depths were physically measured using a transparent measuring gauge. Ice depths were physically measured using digital calipers. Snow density (for determining wc) was measured using a small cylindrical dish with known volume and a weight scale. Table 2 shows the results of the snow- and ice-depth testing.

The sensor does not appear to report accurate snow depths but relatively accurate ice depths, however, only a limited number of tests were completed in this investigation.

Taking the right angle

Initial water depth tests were performed at a sensor installation angle of 37°. The sensor's reported depth measurement range is from 0 to 2 mm. A solid steel mold of known dimensions was used to pond water to specific depths by measuring water volumes applied to the sample. After the initial

Figure 3. CSF, grip measurements and published values on asphalt.

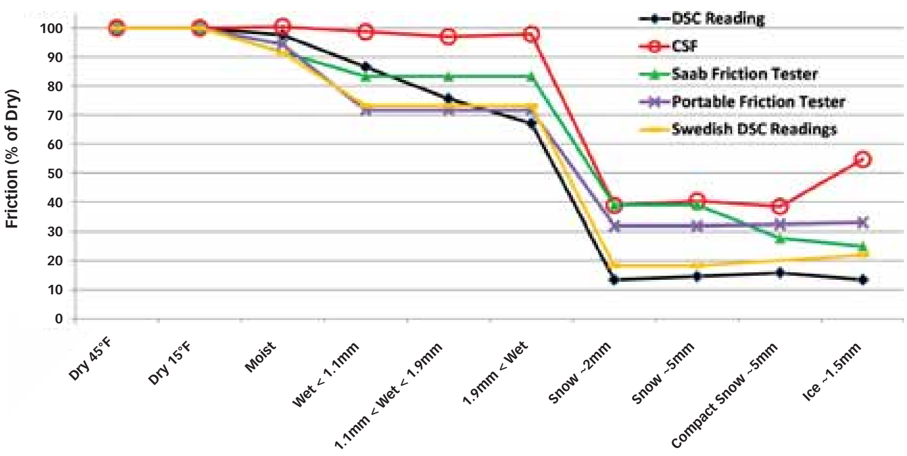


Figure 4. Actual water depth and sensor-reported water depth.

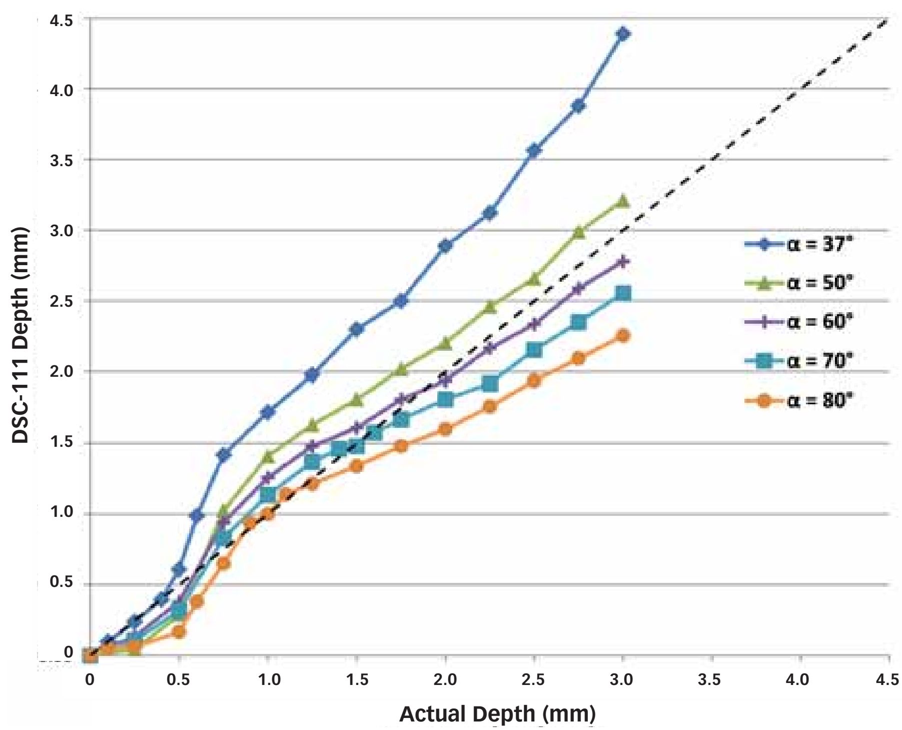


Table 2. Snow and Ice Depth Testing Results

Sample	Actual State	Sensor Reported State	Measured Depth (mm)	Sensor Reported Depth (mm)	Depth Match
Asphalt	Dry	Dry	0.00	0.00	✔
Asphalt	Loose Snow (2 mm)	Snowy	0.37 (wc)	1.01 (wc)	No
Asphalt	Loose Snow (5 mm)	Snowy	0.93 (wc)	1.26 (wc)	No
Asphalt	Compacted Snow (5 mm)	Snowy	2.16 (wc)	1.21 (wc)	No
Asphalt	Ice	Icy	1.4	1.54	✔
Concrete	Dry	Dry	0.00	0.00	✔
Concrete	Loose Snow (2 mm)	Snowy	0.37 (wc)	0.78 (wc)	No
Concrete	Loose Snow (5 mm)	Snowy	0.93 (wc)	0.82 (wc)	No
Concrete	Compacted Snow (6 mm)	Snowy	3.17 (wc)	0.79 (wc)	No
Concrete	Ice	Icy	1.5	1.40	✔

testing at an installation angle of 37°, a calibration test was performed that included testing water depths at installation angles of 50°, 60°, 70° and 80°. The manufacturer stated that the sensor should be installed at an angle between 30° and 85°. Figure 4 shows the results of the testing at the five different installation angles.

None of the installation angles tested was accurate over the range of water depths considered, so a calibration table was developed. This calibration table was to be deemed useful if raw sensor readings could be calibrated to accurate readings based only on the installation angle of the sensor.

Tests to validate this calibration were then performed at installation angles of 45°, 55°, 65° and 75°. Figure 5 shows the results of validation tests.

The results of the validation showed that the calibration was successful. The sensor's water-depth readings could then be calibrated to very accurate water depths based only on knowing the installation angle of the sensor.

Enough to make a decision

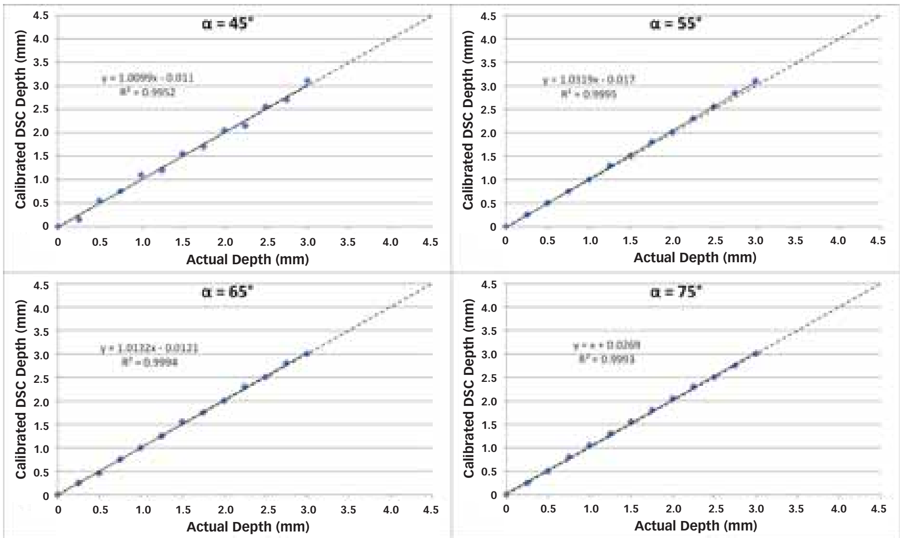
The results of testing the sensors showed that they accurately report the surface state of the roadway for both asphalt and concrete. They output grip readings that show patterns of change in friction consistent with other road-friction metrics. They are not accurate at determining snow depth but may accurately measure the depth of ice present. The depth of water output by the sensors is dependent on the installation angle; no angle tested was accurate for all water-depth ranges tested. A simple calibration was able to correct virtually all errors in water-depth measurements.

Outputs from these sensors may be used to make winter-maintenance decisions or ITS decisions like posting a warning to a dynamic message sign or lowering a variable speed limit. Results from this study suggest that an agency may be justified in using the surface state (dry, moist, wet, snow or ice) as the sole or main driver of decisions. The grip number that aims to express a relative slickness of the road as experienced by drivers may be useful for some decisions, but clear cut-off values that correspond to measurable levels of vehicle performance may not currently exist.

Snow depths do not appear to be an accurate source of information, and ice depth was not tested thoroughly, but it seems unlikely that the exact depth of snow or ice would make much difference for most transportation applications. The presence alone of snow or ice may be more important than the depth of either, and the sensor is accurate at determining the presence of snow and ice.

If the depth of water present on a road surface is an important factor in making decisions (perhaps for hydroplane concerns) then the sensor output can be calibrated to provide relatively

Figure 5. Validation results.



accurate information. If water depths are only for information purposes or for decision support, then perhaps installing the sensors at an angle between 50° and 70° would suffice. Many of these sensors are already installed at RWIS stations around the country, and perhaps using simple calibrations like the one developed in this investigation would provide more accurate measurements for maintenance personnel or ITS systems.

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