Memorandum

SRF No. 10424

To: Clear Roads Project Committee

From: SRF Consulting Group, Inc.

Date: October 25th, 2018

Subject: CR 16-03: Mobile Technologies for Assessment of Winter Road Conditions – Standards Memorandum

Introduction

The availability and accessibility of pavement condition and weather data influences the way maintenance operations occur. A consistent way to convert numerical data into a well-defined description with standard terminology could improve maintenance communications between agencies, departments, and the public. Mobile road weather sensors provide useful information for transportation agencies, but standards and guidelines for interpreting data have yet to be established.

The outputs of mobile pavement sensors may deviate from the needs and expectations of agencies that use the technologies. As the abilities of these sensors continue to improve and mature, manufacturers must utilize input and collaborate with agencies to best guide their research and development toward future products.

This memorandum provides examples of standards for road weather conditions based on previous research, Clear Roads committee recommendations, and data collected from the mobile sensor testing completed in Task 4 of this project.

Accuracy – Expectations and Results

Prior to the testing task, Clear Roads agencies were surveyed about their desired level of accuracy for each measured parameter. Respondents were asked to choose from the following as their desired accuracy: Very Poor Accuracy (10%+ error), Questionable Accuracy (within 10% error), Acceptable Accuracy (within 5% error), Good Accuracy (1-3% error), and Excellent Accuracy (0-1% Error). Table 1 shows the percentage of respondents who chose each level of accuracy for each parameter.

Table 1. Desired Accuracy from Clear Roads Survey Respondents

		Parameter			
		Pavement Temperature	Air Temperature	Relative Humidity	Water Film Height
Desired Accuracy	Very Poor Accuracy (10%+ error)	0%	0%	0%	5%
	Questionable Accuracy (within 10% error)	0%	0%	6%	10%
	Acceptable Accuracy (within 5% error)	4%	9%	17%	**38%**
	Good Accuracy (1-3% error)	**61%**	**59%**	**67%**	**38%**
	Excellent Accuracy (0-1% Error)	35%	32%	11%	10%

Based on the testing performed and data collected, none of the sensors performed within the majority's desired accuracy for any parameter during the testing. The average percent error and preferred percent error are shown in Table 2. Bolded and underlined table items indicate the desired accuracy selected the most for each parameter by survey respondents.

Table 2. Average Percent Error by Sensor and Parameter

		Parameter			
		Pavement Temperature	**Air Temperature**	**Relative Humidity**	**Water Film Height**
	Desired Accuracy	**1-3% Error**	**1-3% Error**	**1-3% Error**	**1-3% Error**
Mobile Sensor	High Sierra	9.6% Error	6.9% Error	13.2% Error	N/A
	Lufft	**5.6% Error**	**3.8% Error**	**9.2% Error**	83.0 % Error
	Teconer	8.3% Error	14.6% Error	N/A	373.2 % Error
	Vaisala	5.8% Error	11.7% Error	15.5% Error	**60.1 % Error**

While the discrepancy between desired and actual percent error is significant, it is important to note that when working with small numbers, a slight difference may give a large percent error. For example, a 0.5ºF difference when the exact temperature is 5ºF generates a 10% error. Teconer's average error of 373.2% for water film height (see Table 2) is an average error of only 0.202mm (Table 3).

Therefore, the average difference between the sensor measurement and the baseline measurement are reported in Table 3 with the parameters' units. In addition to the project testing that was performed, manufacturers reported accuracy values for parameters. The error margin reported by the manufacturer is also included in Table 3.

Table 3. Average Error by Sensor and Parameter (in Parameter Unit)

	Pavement Temperature	Air Temperature	Relative Humidity	Water Film Height
High Sierra Test Runs	3.75ºF	2.55ºF	7.58%	N/A
High Sierra Lab Results	±2ºF	±0.9ºF	±3%	N/A
Lufft Test Runs	2.04ºF	1.39ºF	6.48%	0.171 mm
Lufft Lab Results	±1.44ºF	±0.9ºF	±3%	±10%
Teconer Test Runs	2.94ºF	5.50ºF	N/A	0.202 mm
Teconer Lab Results	±0.6ºF	±0.6ºF	N/A	±10%
Vaisala Test Runs	2.07ºF	4.44ºF	8.38%	0.119 mm
Vaisala Lab Results	±0.6ºF	N/A	N/A	N/A

Testing results had errors much higher than both manufacturer reports and survey results. After testing was completed and the preliminary findings were shown to the Clear Roads Committee, some concern arose that the error was much higher than expected. However, the committee also recognizes the limitations of available technology in real-world roadway conditions. Therefore, it is recommended that manufacturers continue to work on improving accuracy under field conditions on their sensor equipment.

Surface State

Descriptive road conditions are a key piece of information for drivers and agencies alike. To make safe, smart decisions, it is necessary to distinguish between types of surface states. Each of the four sensors tested in this project measures surface state, but they report these states using different terminology. The terms used to report surface state by each sensor are listed in Table 4. All devices use optical sensors to determine surface state, but the exact method differs between devices. Some devices also use other parameters, such as friction or water film height, to validate the optical readings. After speaking to Clear Roads members, most expressed that they felt each sensor measured too many surface states. When making decisions, the technical committee indicated that maintenance staff typically only distinguish between Ice, Snow, Wet, or Dry.

Table 4. Surface State Conditions Measured by Each Sensor

Vaisala	High Sierra	Teconer	Lufft
Dry	Dry	Dry	Dry
Moist	Damp	Moist	Damp
Wet	Wet	Wet	Wet
Frosty	Freezing Wet	Slush, Ice or Snow with Water	Water + Ice
Snowy	Snow	Snow or Hoar Frost	Snow - Covered
Icy	Ice	Ice	Ice-Covered
Slushy	Slush		Snow-/Ice-Covered
			Chemically Wet

In addition to sensor vendors, other attempts have been made to define or summarize road conditions through a variety of means. Qualitative definitions, often using images or descriptive language, are common. Figure 1 provides an example from Bandara[1] to demonstrate terminology based on a visual reference.

[1] Bandara, N. Pilot Study: Pavement Visual Condition and Friction as a Performance Measure for Winter Operations. 2014. http://docs.trb.org/prp/15-0574.pdf

Figure 1. Visual Winter Road Condition Determination Guide (Bandara, 2014)

Surface Condition	Description	Picture
Bare	Bare Pavement	
Centerline Bare (CL Bare)	Entire lane is cleared of snow, ice and slush.	
Wheel Track Bare (WT Bare)	Only wheel tracks are bare, snow/ice/slush in the other areas	
Loose Snow/Slush (Loose Snow)	Loose snow/slush covered	
Snow Covered (Snow)	Entire roadway is covered with packed snow and ice	

Using images from video footage taken during test runs, a qualitative set of surface state definitions were created. Images were selected from time periods where sensors were in agreement about surface state type. Due to the differences in terms between each sensor and comments received from the Clear Roads committee, Table 5 focuses on Dry, Snow, Wet, and Ice.

Table 5. Surface State Recommendations

Surface State	Definition	Image
Dry	Pavement has not been exposed to water for 24 hours. Pavement has been uncovered and allowed to air dry during the previous 24 hours.	
Snow	At least 5 mm of accumulated and unplowed snow.	
Wet	Pavement has a water film thickness of at least 0.5 mm.	

Surface State	Definition	Image
Ice	Frozen water with a film thickness of 0.5 mm or greater	

Each sensor reported additional surface states such as damp, moist, critically wet, etc. However, Clear Roads committee members identified that they prefer a short, basic list of surface states with clear definitions. This allows quick, easy, and simple translation of data for public consumption.

Grip Standards

Friction correlates to driving safety conditions such as wheel slip and stopping distance. The Idaho and Colorado State DOTs use several variables including road friction to calculate their version of a Weather Severity Index (WSI). Idaho uses a Vaisala DSC111 sensor for their friction readings, and classifies the friction intervals by mobility impact[3]:

[3] ITS International. 2013. "Idaho Finds the Right Formula for Winter Maintenance." http://www.itsinternational.com/categories/travel-information-weather/features/idaho-finds-the-right-formula-for-winter-maintenance/

Table 6. Idaho DOT Mobility Impact by Friction Interval

Friction Interval	Mobility Impact
0.6 and above	Normal Mobility
0.5 – 0.6	Slight Mobility Reduction
0.4 – 0.5	Moderate Mobility Reduction
0.3 – 0.4	Vehicles may start sliding off the road
0.3 and below	Multiple vehicle slide-offs possible; mobility greatly affected

Based on testing results, the friction coefficient for even, dry, pavement is often given as 0.81 or 0.82. All four sensors studied use one of those values as the corresponding value as the maximum friction in their device user guides. The devices report and utilize the friction coefficient differently. The Vaisala device gives a grip "warning" at friction values at or below 0.6 and a grip "alarm" at or below 0.4. These values can be manually changed at the user's discretion. The other devices do not have set numerical values at which an alert or warning is given, though the High Sierra IceSight does report Good, Fair, or Poor grip depending on friction readings and other parameters.

Several studies have been conducted on modeling and classifying the relationship of the impact of friction on road safety. A Swedish 2001 review of friction and traffic safety by Wallman and Åström[4] categorizes friction readings by accident rate as shown in Table 7. The study measured surface friction and determined the accident rate of a small length of roadway.

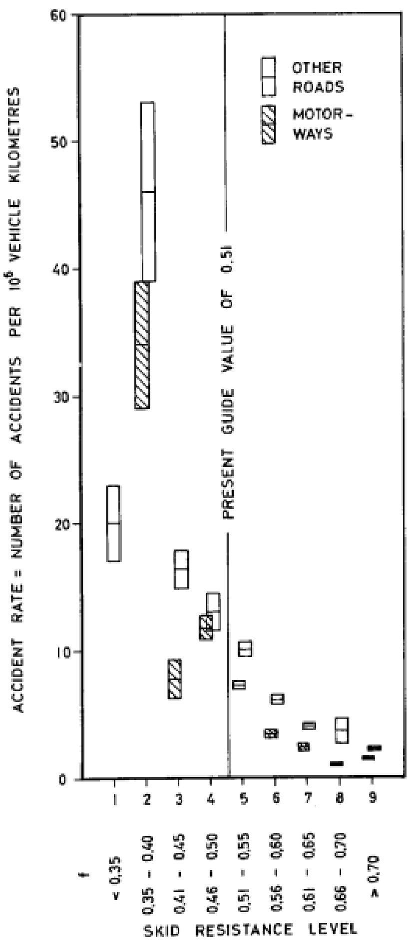
Table 7. Table from Wallman and Åström, Accident Rate (Personal Injuries per Million Vehicle Kilometers) by Friction Interval

Friction interval	Accident rate
< 0.15	0.80
0.15 – 0.24	0.55
0.25 – 0.34	0.25
0.35 – 0.44	0.20

[4] Wallman, Carl-Gustaf and Henrik Astrom. 2001. "Friction Measurement Methods and the Correlation Between Road Friction and Traffic Safety: A Literature Review. *Swedish National Board and Transport Institute.* http://vti.diva-portal.org/smash/get/diva2:673366/FULLTEXT01.pdf

Similarly, a regressive analysis performed on historical data in Germany produced the graph in Figure 2 of accident rates and friction levels:

Figure 2. Figure from Wallman and Åström, Accident Rate (Personal Injuries per Million Vehicle Kilometers) by Friction Interval



Using a cumulative distribution function of the German study, it was found that approximately 50% of accidents took place at friction levels of under 0.4, and around 92% of accidents took place at friction levels under 0.6.

Both Table 7 and Figure 2 show that decreasing friction results in an exponential increase of accident rates. However, because friction is unitless and varies depending on testing device, data will vary between studies. Additionally, many factors contribute to accident rates beside friction, such as location, pavement type, visibility, and lane widths.

During testing, friction values would quickly rise and fall between high and low friction values for all sensors. Surface conditions rapidly shifted over just a short segment of roadway, making it difficult to assign a small range of friction for a section of pavement. Thus, while basic concepts of friction and grip can be applied generally to results, the current method of reporting friction makes treatment decision making and standardization difficult.

For winter maintenance agencies, friction reporting, like that shown in Table 7, would provide the most useful information for decision making. Additionally, techniques to generalize friction values like those used by the Vaisala and High Sierra sensors now are also acceptable. Reporting only numerical values at a high frequency makes it difficult for operators in the field to make real-time decisions. Generalized values are more practical for field use as they require little to no data interpretation to use.

Grip and Surface State Relationship

While surface state and grip are frequently measured against visual assessments and safety parameters, respectively, they also have been studied relative to one another.

Some agencies, such as the Finnish National Road Administration (Finland) and the Hokkaido Development Bureau (Japan), have adapted this approach, as shown in Figure 3[5].

Figure 3. Table from Fu et al., Road Surface Conditions and Friction Coefficients by Agency

Sweden		Finland		Japan, Hokkaido	
RSC categories	Friction coefficients	RSC categories	Friction coefficients	RSC categories*	Friction coefficients
• Good • Medium to good • Medium • Medium to poor • Poor	• 0.40 and above • 0.36–0.39 • 0.30–0.35 • 0.26–0.29 • 0.25 and below	• Bare and dry • Bare and wet • Packed ice and snow • Tightly packed snow • Icy • Wet ice	• 0.45–1.00 • 0.30–0.44 • 0.25–0.29 • 0.20–0.24 • 0.15–0.19 • 0.00–0.14	• Dry, Wet • Slush, Granular snow on ice crust, Powder snow • Compacted snow, Granular snow on ice crust • Ice film, Powder snow on ice crust, Ice crust • Very slippery compacted snow, Very slippery ice crust, Very slippery ice film	• ~0.45 • 0.25–0.35 • 0.2–0.3 • 0.15–0.3 • 0.15–0.20 • ~0.20 • ~0.15

The reported conditions and corresponding friction values in Figure 3 are a good representation of systems used for agencies using friction as a means to define pavement conditions. Friction values may correspond to condition type, like in the case of Finland and Japan, or an assessment of overall condition quality, like Sweden. Grouping friction rate by condition type allows for a simple visual assessment of conditions. Grouping by road condition quality requires friction measurements but places the importance directly on impact to drivers. However, because friction is unitless, results

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[5] Fu, Liping et al. 2016. "A risk-based approach to winter road surface condition classification" *NRC Research Press.* March 2016. http://web.a.ebscohost.com.ezp2.lib.umn.edu/ehost/pdfviewer/pdfviewer?vid=1&sid=da67800f-47b1-4d84-aeaa-62a38af3d8ea%40sessionmgr4010

depend on the testing device and conditions, making it difficult to replicate results between various sensors.

The range of friction for a sensor's corresponding surface state during the 26 test runs performed as part of this project are shown in Table 8. Not all surface states were encountered during test runs, and therefore no data is included for those states. The High Sierra and Vaisala sensors have a wider range of friction detected for each state and rely on optical readings to make surface state determinations. The Lufft and Teconer sensors appear to have a more defined friction range for each surface state, similar to the approach shown in Figure 3 of Hokkaido, Japan. However, the variability and range of each sensor's friction reading is too high to effectively categorize surface state by friction.

Table 8. Surface State and Corresponding Friction Range

Vaisala		High Sierra		Teconer		Lufft	
State	Range	State	Range	State	Range	State	Range
Dry	.19-.82	Dry	.1-.82	Dry	.39-.81	Dry	.82-.82
Moist	.26-.82	Damp	.12-.82	Moist	.35-.81	Damp	.8-.82
Wet	.48-.82	Wet	.1-.82	Wet	.32-.75	Wet	.55-.8
Frosty	Not Measured	Freezing Wet	Not Measured	Slush, Ice or Snow with Water	.19-.72	Water + Ice	.7-.81
Snowy	.09-.77	Snow	.1-.82	Snow or Hoar Frost	.21-.58	Snow - Covered	Not Measured
Icy	.09-.71	Ice	.1-.78	Ice	.15-.81	Ice-Covered	.13-.81
Slushy	.44-.78	Slush	.12-.62			Snow-/Ice-Covered	.22-.55
						Chemically Wet	.77-.82

The range of friction values for a given surface condition is typically too wide to provide value for a winter maintenance decision process. Enabling meaningful use of mobile sensor data will require both a more consistent output of friction values for a given surface condition and standardizations of reported conditions across manufacturers.

Sensor Maintenance

Each manufacturer recommends similar maintenance procedures. All manufacturers recommend periodic checks the devices to ensure the lens is clear and reading values correctly. If the sensor is dirty, manufacturers suggest using a gentle, damp cloth with mild detergent to clean the lens. Vaisala and Lufft also suggest checking mounting, cables, screws, etc. regularly for looseness or damage.

The Vaisala DSP310 also requires a yearly filter change in the humidity probe and a yearly calibration of the probe at their labs. High Sierra suggests a calibration check at every maintenance visit. High Sierra also offers an annual service plan option for an additional cost.

Testing took place from December 2017 to April 2018. During this period, no additional maintenance besides the recommended cleaning was performed. It is highly recommended that mounting is checked and secured frequently to ensure that sensors do not become detached from their mounts as a result of excessive vibration.

Summary

Accuracy

None of the parameters measured by any of the sensors met the accuracy levels desired by most Clear Roads survey respondents. Lufft had the lowest percent error in air temperature, surface temperature, and relative humidity, and Vaisala had the lowest error for water film height (See Table 2). The percent error can be very large when working with small numbers, such as the ones measured for water film height. Table 3 provides the average error in the parameters' units and compares it to the errors found by vendor testing in lab conditions. As technology advances, the Clear Roads committee desires percent errors closer to the survey results values which are outlined in Table 1.

Surface State

Methods to define surface state vary by agency. Many surface states are reported by each sensor, but committee members indicate that most transportation agencies prefer only four basic states; Ice, Snow, Wet and Dry. Recommended definitions for each of these states are provided in Table 5.

Grip Standards

Friction has a negative exponential relationship to accident rate, but due to the inconsistencies between friction measurement methods, a standard to relate friction measurement to mobility effects across all four sensors cannot be developed. For each sensor, it is recommended that friction readings also be grouped in 3 to 5 levels of mobility or safety so that quick, informed decisions can be made in the field.

Grip and Surface State Relationship

The relationship between surface state and grip is often presented as a range of friction coefficient values to a type of surface state, like those shown in Figure 3. When analyzing friction values by surface state from testing, most surface states had a broad range of friction values. This does not mean the values are inaccurate, but as with grip standards alone, they do not provide useful information for timely field decisions. As such, it is recommended that future sensors generalize and remove outliers before reporting so that data can be quickly and easily interpreted in the field.

Recommendations

To ensure clear communications with the public and make cost-effective decisions about roadway treatment, a simple, definitive rubric is best suited for the needs of transportation agencies. While a generalized rubric may result in a loss of precision, it also allows for more practical use. Using the values from previous studies, suggestions from the Clear Roads committee, and testing results, a table was created as an example of such a rubric. The Clear Roads committee suggests that this type of approach be utilized in future sensors. The exact values of friction and verbiage may change based on findings of individual developers but reported conditions would resemble those shown in Table 9.

Table 9. Recommended Mobility, Surface State, and Friction Rubric

Road Surface Condition	Surface State	Friction Value
Poor	Ice	<0.2
	Snow	0.2-0.4
Medium	Wet	0.4-0.7
Good	Dry	>0.7

Table 10 combines the recommendations of Table 9 with additional definitions and imagery for the indicated surface states.

Table 10. Recommended Rubric for Sensor Reporting

Road Surface Condition	Surface State	Definition	Image	Friction Value
Poor	Ice	Frozen water with a film thickness of 0.5 mm or greater		<0.2
	Snow	At least 5 mm of accumulated and unplowed snow.		0.2-0.6

Road Surface Condition	Surface State	Definition	Image	Friction Value
Medium	Wet	Pavement has a water film thickness of at least 0.5 mm.		0.6-0.8
Good	Dry	Pavement has not been exposed to water for 24 hours. Pavement has been uncovered and allowed to air dry during the previous 24 hours.		>0.8

Air temperature, surface temperature, relative humidity, and water film height are reported in a more consistent fashion. However, none of the parameters currently meet the "good accuracy" standard desired by Clear Roads survey respondents. There also appears to be a discrepancy between manufacturer's claimed accuracy, which is likely obtained in a controlled environment and observed performance under field conditions. An improvement in accuracy particularly in "real world" use cases would improve the usefulness of sensors when making maintenance decisions.

Conclusion

Mobile road weather sensors can provide useful data to transportation agencies. The differences across sensors and the high variability in their readings make establishing universal standards difficult. This memorandum provides examples of previous methods of standardizing these data and recommends future areas of improvement for sensors.

Combining feedback from Clear Roads, test results, and previous research, recommendations for future sensors were developed. First, categorizing grip, surface state, and mobility impact into a few basic levels as shown in Table 9 would provide agencies with information more suited for everyday consumption. Additionally, Clear Roads requests the accuracy of air and pavement temperature, relative humidity, and water film height continues to improve, and that manufacturers consider the accuracy of sensors in the field in addition to the lab.

As Mobile Road Weather Information Systems improve and are used more often in winter maintenance, these recommendations will help serve both manufacturers and agencies alike to ensure the best product with the highest possible satisfaction.