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Evaluation of Two New Vaisala Sensors for Road Surface Conditions Monitoring

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Publication Title	# Evaluation of Two New Vaisala Sensors for Road Surface Conditions Monitoring

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Abstract	This report describes the results of an investigation concerning the performance of two new Vaisala pavement sensors for monitoring road surface conditions. Road surface condition data reported by the Vaisala sensors were compared to those by traditional in-situ pavement sensors and visual observations. In addition, grip levels estimated by Vaisala sensors were compared to real surface friction measurements taken by a continuous friction meter. Based on the limited field observations, it was found that 1) the Vaisala sensors were reliable and accurate in determining road surface contaminants; 2) there were systematic differences in temperature measurements between the Vaisala sensor and the traditional in-situ Lufft sensor; and 3) the grip levels reported by the Vaisala sensor did not correlate well with the observed friction measurements.
Key Words	Road Weather Information System (RWIS); friction measurement; road surface condition monitoring
Distribution	

Ontario

Ministry of Transportation

Evaluation of Two New Vaisala Sensors for Road Surface Conditions Monitoring

August 2005

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Introduction

The purpose of this project was to evaluate the performance of two new remote optical sensors (collectively called Vaisala Spectro/Cyclo sensors), namely, Vaisala Remote Road Surface State Sensor (DSC111) and Vaisala Remote Road Surface Temperature Sensor (DST111), as shown in Fig.1.

DSC111 is an active near-infrared band (-1 µm) remote sensor, which sends infrared light beams to the road surface and detects the backscattered signals at selected wavelengths. Based on observed difference in light absorption, it can differentiate pavement contaminant layers and thus surface state such as dry, moist, wet, icy, snowy/frosty or slushy [1]. The sensor also provides a measure called grip level which is intended to represent the level of friction of the road surface. This grip level is estimated using an empirical model based on the surface state and contaminant depth detected by the sensor [2]. DSC111 reports the following data items:

- Pavement states: dry, wet (thin water layer), slushy (thick water layer, no ice or snow), snow or frost (white ice), ice (black ice)
- Pavement contaminant depth in equivalent liquid water amount (in mm)
- Estimated surface grip level (0.01-1.00)

DST111 is a temperature sensor based on infrared technology. It measures the difference of long wave infrared radiations between the sensor instrument itself and the road surface. This difference can be calibrated to a known temperature difference and thus used to estimate the pavement temperature. According to its product specifications, DST111 is accurate up to 0.3 ºC in typical icing conditions [1]. The detailed specifications for DSC111 and DST111 are attached in Appendix A. A DST111 report includes the following data:

- Pavement surface temperature in ºC
- Air temperature in ºC
- Dew point temperature in ºC
- Relative humidity in percentage

(a) DSC111 (Spectro sensor)

(b) DST111 (Cyclo Sensor)

Figure 1: Vaisala Spectro/Cyclo Sensor Suite

Study Site and Test Arrangements

One set of Vaisala Spectro/Cyclo sensor suite was installed on the eastbound lanes of Highway 417 near Casselman, Ontario, as shown in Figure 2. The sensors are installed on a pole at the roadside and are vertically 8.3m over the road way level. A 20cm-diametered road surface area near the right wheel track of the lane was monitored. The installed sensors and the monitored area are shown in Figure 3.

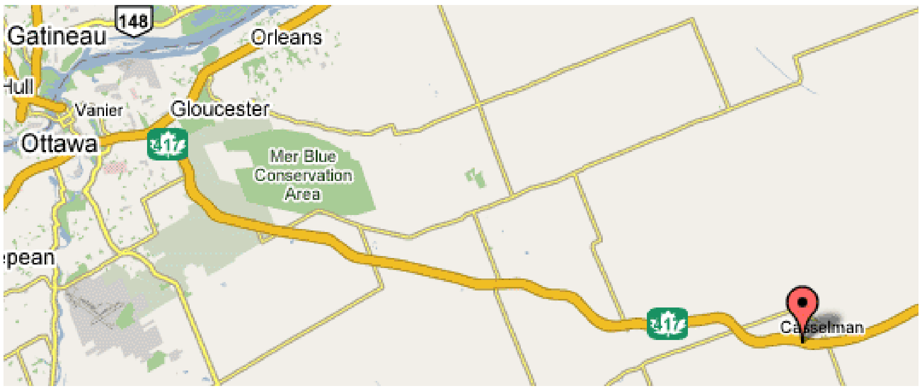

Figure 2: Vaisala Sensors' Location

Figure 3: Sensor Installation and Monitored Area

A traditional Lufft IRS-20 in-situ pavement sensor, located about one meter away from the spot monitored by the Vaisala sensors, also reports real-time road surface state as well as pavement temperature. The close proximity of these two types of sensors ensures that a valid comparison between their measurements can be made. The reporting frequency of both sensors is 20 minutes.

Four major snowstorms in winters of 2007 (Feb.14 and Mar.2) and 2008 (Feb.1-2 and Feb.6-7) were monitored closely for this study. Data on road surface state and temperature reported by the Vaisala sensor suite and the in-situ pavement sensor during the storm periods were collected and compared.

The study section has a new asphalt pavement surface resurfaced prior to the start of this project (end of 2006). As the new asphalt surface was much darker than a regular asphalt surface, the Vaisala sensor suite, which works under an optical mechanism, experienced large systematic errors. A series of onsite calibrations had to be performed during first three months after the installation. The data used in this analysis were collected after the calibration.

Concurrently, a series of friction tests were conducted at the study section. A detailed description about this test can be found in [4]. The friction coefficients measured in the lane of the monitored area when the friction trailer passing the monitored area were compared to the estimated grip level by DSC111 at the closest reporting time.

Test Result I: Road Surface Temperature

Fig. 4 shows the time series of temperatures measured by DST111 and the Lufft sensor over five days from Feb. 27 to Mar. 3 of 2007. It can be observed that while both sensors had captured the general trend of temperature variation, there were clearly systematic differences between the two readings. For example, the temperatures from the DST111 sensor were consistently lower than those from the in-situ sensor over noon periods with a maximum difference as high as 3 ºC. At other time periods of the day, the difference was much smaller. Two additional examples, shown in Fig. 5 and 6, further confirmed this systematic discrepancy between these two sensors.

To statistically verify this observation, we conducted a pair-wise comparison between the temperatures measured by these two sensors for the months from Dec.15, 2006 to Mar.7, 2007. The detailed statistics are provided in Appendix D. It was found that the difference in the mean temperatures between these two sensors was statistically significant at a level of significance close to 5%. However, the mean differences were all less than 1ºC.

The differences in temperature readings were also grouped by range of absolute temperatures and then evaluated statistically (**Appendix E**). Figure 7 shows the difference in temperature measured by these two sensors based on the temperature data of Dec.2006~Mar.2007. A clear systematic pattern in measurement discrepancy emerges. Compared to the Lufft in-situ sensor, DST111 gave significantly higher temperature readings under low temperatures and lower readings under higher temperatures. This difference decreased as the temperature increased. When the temperature was close to 0 ºC, the difference became insignificant. This pattern persisted in all four months. One week's temperature data in winter of 2008 (Feb.1~Feb.7, 2008) is random selected, and the measured surface temperature difference shows similar pattern as the boxplot illustrated in Figure 8.

While it is unknown which sensor actually gave the ground truth measurements, we provide two speculative explanations to the differences. The first is that the temperature readings from the in-situ sensor are those of the pavement surface layer or structure itself instead of the surface contaminants as measured by the DST111 sensor. Therefore, when there were contaminants on the pavement, DST111 and in-situ sensor could be measuring the temperature of different objects. Another explanation is that the DST111 sensor might be influenced by level of solar radiation which may have caused the temperature being dependent on time of day.

Although two sensors gave different ground temperature measurement values, the correlation between them were very high, which is shown in Figure 9.

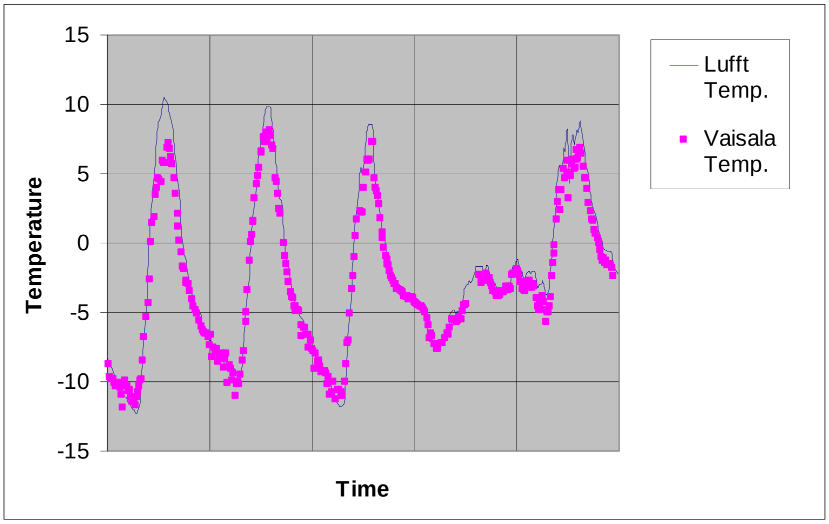

Figure 4: Comparison of Temperature: Vaisala Sensors vs. Luft In-situ Sensors

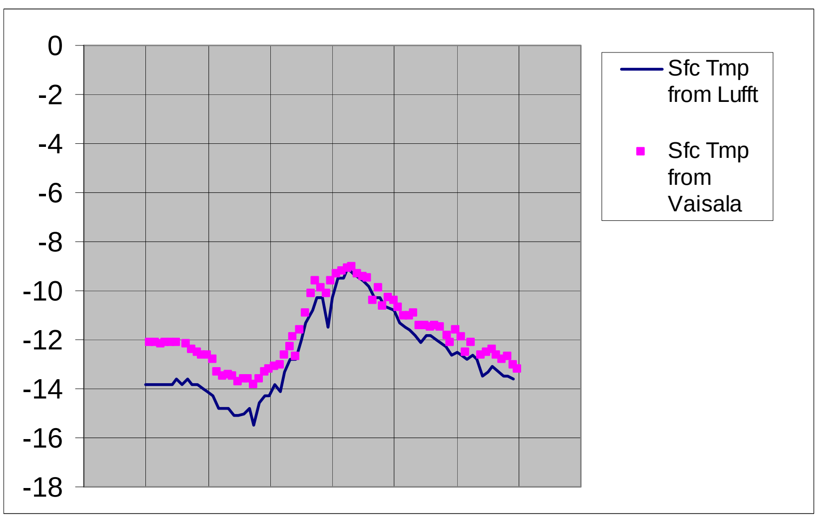

Figure 5: Overestimation of Temperature as Compared to Lufft In-situ

Comment [I1]: Double check please

Sensors (Feb.14, 2007)

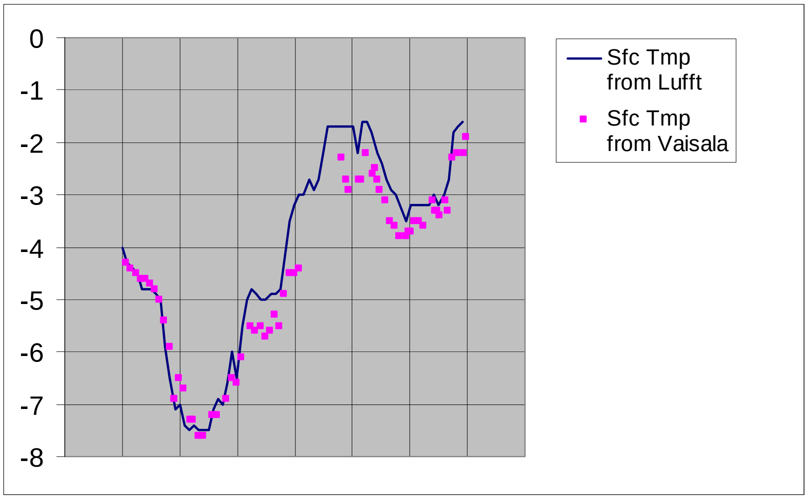

Figure 6: Underestimation of Temperature as Compared to Lufft In-situ Sensors (Mar.2, 2007)

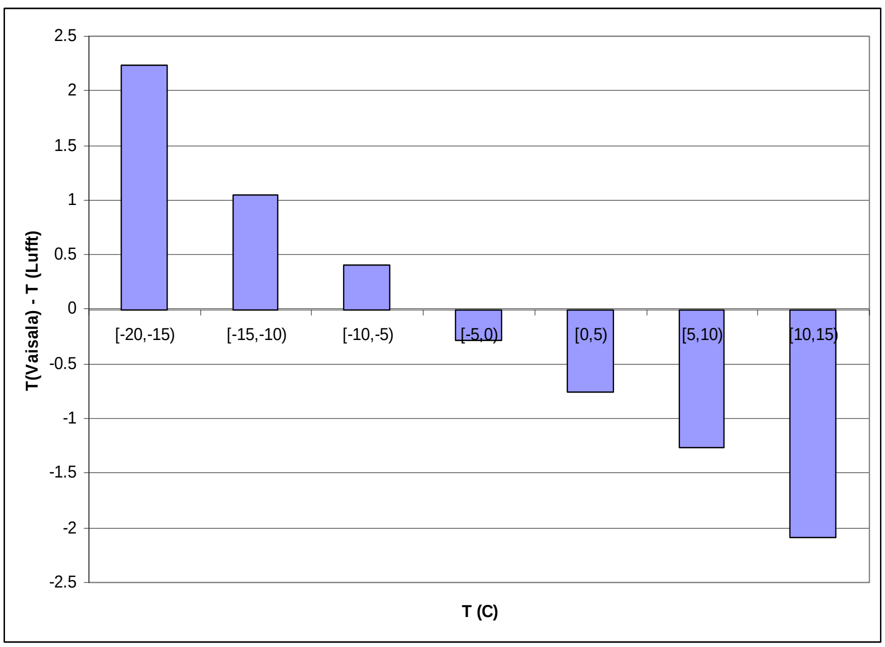

Figure 7: Measurement Difference as a Function of Temperature (winter 2006 ~ 2007)

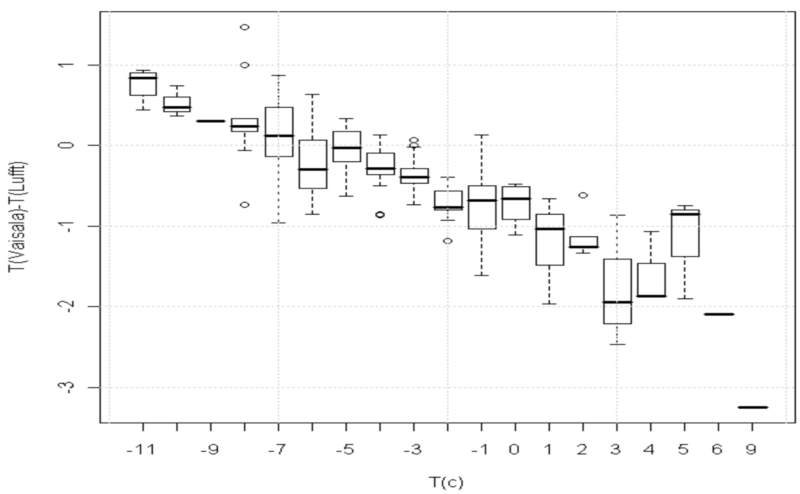

Figure 8: Measurement Difference as a Function of Temperature (Feb.1~7, 2008)

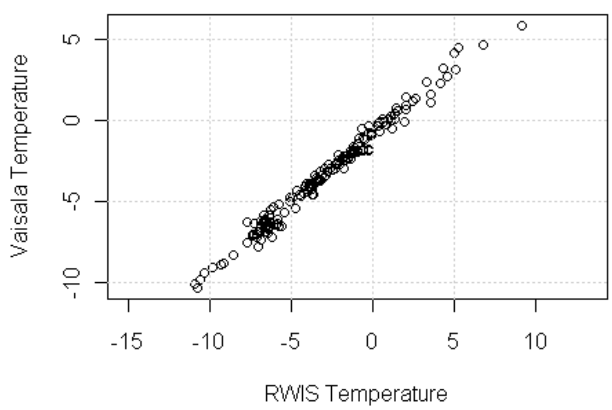

Figure 9: Vaisala vs. RWIS Surface Temperature Readings (Feb.1~7, 2008)

Test Result II: Road Surface State

In order to evaluate the performance of DSC111 for surface state monitoring, videos taken over 25 friction measuring runs in winter 2007 and 13 friction measuring runs in winter 2008 were scanned and the surface state of the monitored area were identified and classified into one of three types, namely, bare dry, wet and snowy/icy. The surface states reported by DSC111 at the closest reporting times were compared to the video-based observations and the results are included in **Appendix B**. In only one out of 25 cases in winter 2007, the surface state reported by DSC111 mismatched with those from the in-situ sensor, which gave a matching rate of 96%. In 2 of 13 cases in winter 2008, the surface state reported by DSC111 mismatched with those from the in-situ sensor, which gave a matching rate of 85%. In all three mismatching cases, Vaisala underestimated the road condition severity compared to the in-situ sensor, i.e. Vaisala reported moist condition while the in-situ sensor reporting snow/ice condition.

The surface state data reported by DSC111 during two snow storms on Feb.14 and Mar.2, 2007 were compared with the in-situ sensor as well. During these two days, the in-situ sensor reported snowy/icy state all the time without any exception. But DSC111 gave a wide range of variable surface conditions including dry, wet, slushy, snowy and icy states, which was consistent with our observation of the video data and MTO's bare pavement reports. This result has also confirmed the finding of a study conducted in North Dakota of USA [6], which suggested that the inability for in-situ sensor to detect varied road surface states during a snow storm is because some contaminants (e.g. snow and ice) could have been compacted over the probe of the in-situ pavement sensor by traffic and maintenance vehicles.

Test Result III: Grip Level

Grip level is an index for road slipperiness that DSC111 reports according to the road surface state. The grip level is a value estimated using an empirical function based on the type and depth of the pavement contaminant such as slushy water, snow or ice. To gain an intuitive view of how the grip level is related to other condition factors, time series of grip level and road surface state data were shown in Figure 10 and 11. It can be observed that the presence of snow and ice corresponded to lower grip levels. In fact, in most cases a road surface covered by snow/ice yielded a grip level of 0.2 or lower. On the other hand, when the surface was free of snow and ice, either dry or covered by water only, the grip level was always high with a value around 0.8. Few intermediate values ranging from 0.2 to 0.8 were obtained, suggesting that the grip measure is not sufficient sensitive to reflect varied snowy/icy conditions.

To evaluate how well the grip measure reflects the actual friction level of a road surface, a series of friction runs were conducted to collect the real friction data at the test site. The friction measurements were obtained using a device called Traction Watcher One (TWO) [5]. A total of 16 runs passed the lane of the monitored area by the Vaisala sensor suite. Each friction measurement was compared to the grip level reported by DSC111 at the time close to when the friction was measured. Figure 12 shows the grip level provided by DSC111 and the corresponding coefficient of friction obtained by the TWO friction meter. Except for these two high friction measurements, there appeared to be little correlation between grip levels and friction measurements.

In order to reduce the effect of random variation, grip levels were aggregated and then compared. In Figure 13 each friction measurement was plotted against averaged grip level over the hour when the friction measurement was taken. While the aggregation improved the overall correlation between grip level and friction, the grip level did not differentiate road surface conditions of varied degree of friction under low friction conditions.

Figure 12 and 13 were plotted according to the friction data of 2007 and the friction data of 2008 are also attached in Appendix C, which didn’t show significant correlation between Vaisala grip level and TWO friction measurements either.

Lastly, the data from the Vasaila sensors are spot specific. As a result, there is an issue on how well these measurements can represent the overall conditions of a maintenance route or the segment close to the monitored spot. Figure 14 and 15 gave two examples of spatial variation of friction data. It can be clearly seen that even over a small range of a few hundred meters the variation is too large to be captured by spot measurements.

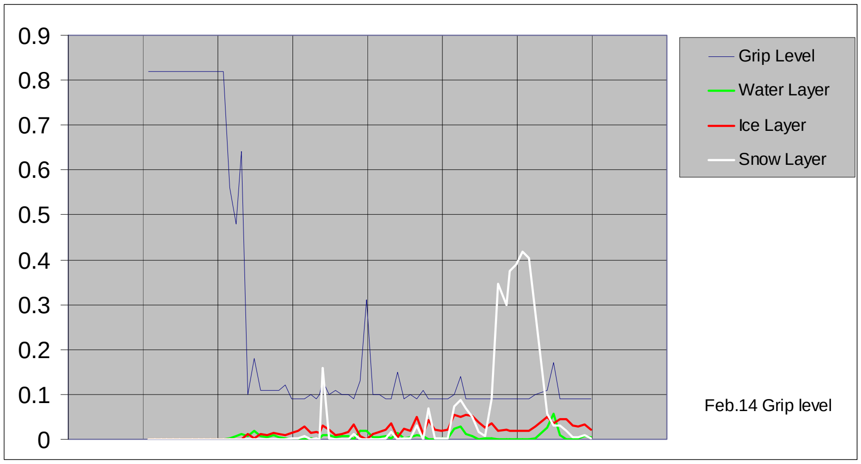

Figure 10: Grip Level and Surface State (Feb.14, 2007)

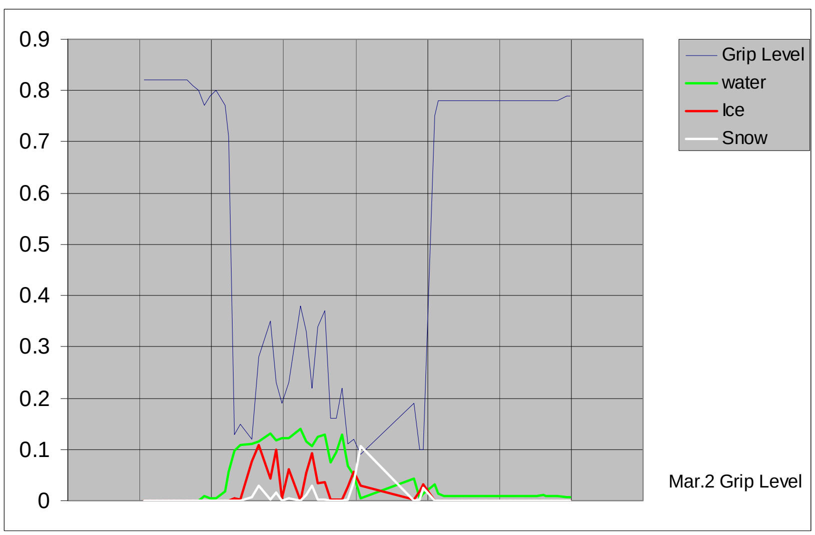

Figure 11: Grip Level and Surface State (Mar.2, 2007)

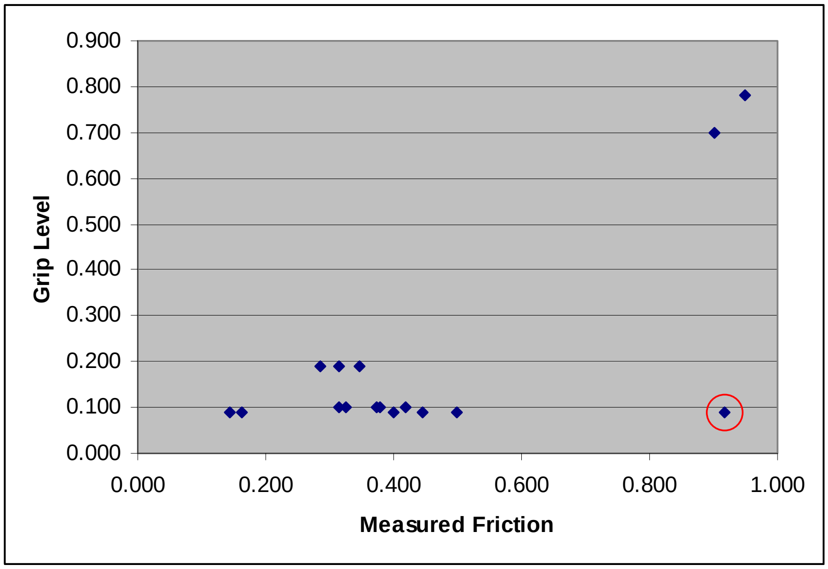

Figure 12: Grip Level vs. Measured Friction

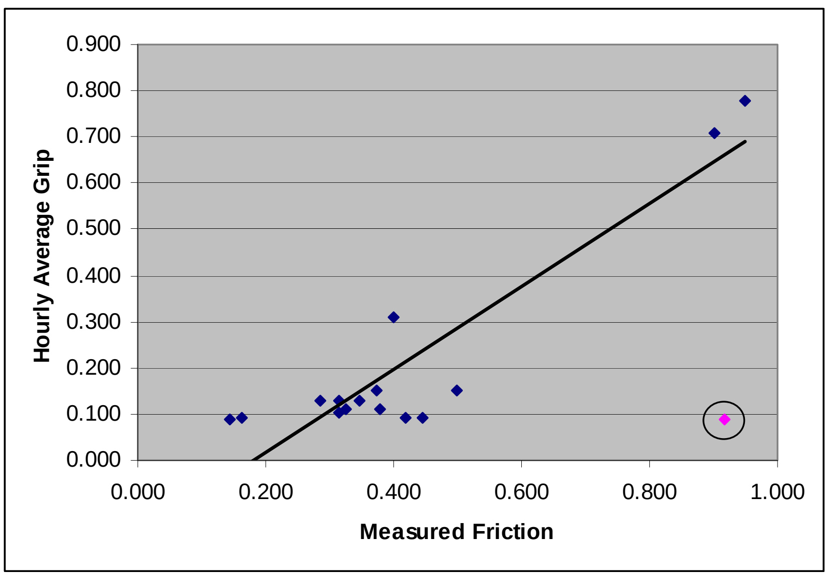

Figure 13: Hourly Averaged Grip vs. Measured Friction

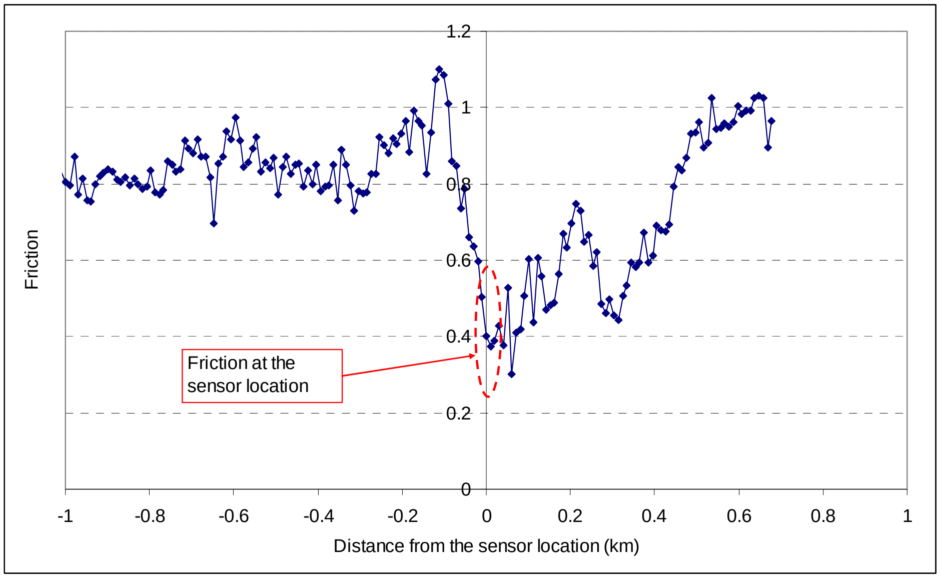

Figure 14: Friction measurements close to the sensor location (8:30am, Feb. 15, 2007)

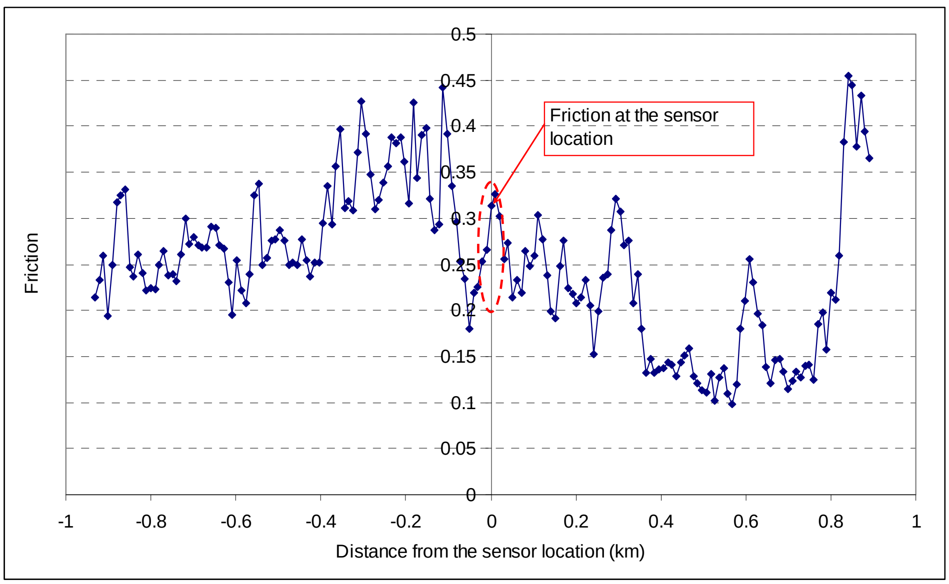

Figure 15: Friction measurements close to the sensor location (3:00pm, Mar. 2, 2007)

Conclusions

This project evaluated the performance of two new Vaisala sensors, namely, DSC111 and DST111, for monitoring pavement surface state and temperature. The major findings of the research are summarized as follows:

- The surface temperature measurements by DST111 were compared with those of the Lufft IRS-20 in-situ pavement sensor. Some systematic differences were found with magnitude depending on temperature range. Compared to the Lufft in-situ sensor, DST111 gave higher temperature readings under low temperatures and lower readings under higher temperatures. This difference decreased as the temperature increased. When the temperature was close to 0 ºC, the difference became insignificant. Although this systematic difference was statistically significant, the absolute value of the difference was mostly less than 2 ºC , which implied the temperature measures of DST111 and Lufft IRS-20 were very close to each other. Additionally, their measurements are highly correlated in a linearly manner, therefore, to a large degree, the measures of these two sensors justified each other

- Based on direct observations of road surface conditions recorded by video cameras, the surface states reported by DSC111 were found accurate with high matching rate. Some underestimations of the road condition severity by the DSC111 happened due to its small monitoring area and the resulting temporally high-variant road condition reporting.

- The grip levels reported by DSC111 were compared to the friction coefficients measured by a friction meter at the same location and time interval. It was found that the correlation between grip levels and frictions were very weak, especially under conditions of low friction. This finding suggests that the DSC111 cannot be used as a reliable replacement of friction measuring equipment.

It should be pointed out that this research was based on data collected over a few snow storms in a single winter season. Further field tests are recommended to substantiate the above findings.

Comment [I2]: A bit more details on overestimation and underestimation

References

[1] Yrjö Pilli-Sihvola etc. “New Approach to Road Weather Measuring Slipperiness.” SIRWEC 2006.

[2] Memos of telephone meetings and email contacts with Paul Bridge (Applied Meteorologist of Vaisala), 2007.

[3] Memos of telephone meetings and email contacts with Peter M Szilagyi (EDP of MTO Eastern Region Operations, Ottawa Contracts Office), 2007.

[4] Matthew Cloutier and Laura Donaldson, “Applicability of Winter Friction Measurements in Ontario.” A project report of 2006-2007 Winter Maintenance Technology Program, 2007.

[5] Manual of Traction Watcher One, http://www.pon-cat.com/

[6] Jeff Tilley and Luke Johanneck, “Evaluation of Vaisala Spectro Pavement Sensor”, Preliminary Report for Aurora Project 2006-04, August 20, 2007.

Appendix A: Specifications of Vaisala Sensors

VAISALA

Vaisala Non-Invasive Pavement Surface State Sensor DSC111 (Spectro)

Features and Benefits

- Non-invasive remote surface state sensing
- Spectroscopic measuring principle, identifying the presence and thickness of:
  - Water
  - Ice
  - Slush
  - SnowFrost
- Unique measurement of road friction or grip
- Accurate and stable measurement results even with intense traffic
- Eye-safe laser technology
- Easy installation and service
- Low maintenance costs
- Weather-proof, durable design
- Easy integration with Vaisala ROSA Road Weather Station, or can operate as a stand-alone solution with solar/gsm options
- NTCIP compliant when used with Vaisala DMC interface card

The unique Spectro sensor eliminates the service disruption which was previously associated with the installation of a road weather station. The remote installation means that there is no requirement to slot-cut the surface or close the road. The sensor may be installed in a remote location on a pole adjacent to the road, or as an addition to the Vaisala ROSA Road Weather Station.

The spectroscopic measuring principle enables accurate measurement of the amounts of water, ice, and snow. Water and ice are measured independently of each other, enabling Spectro to accurately report the surface state.

Spectro provides an accurate measure of the presence of ice crystals well before they cause the road to be slick. The Winter Maintenance engineer is therefore able to monitor even the smallest changes in grip in order to take the appropriate remedial action.

The water reading is useful for advanced warning of hydro-planing.

Spectro has proven its capabilities during three years of intensive field testing in collaboration with Vaisala customers.

Together with Cyclo, which remotely measures surface temperature, Spectro forms a versatile stand-alone weather station.

Vaisala Inc., Boulder Operations
P.O. Box 3659, Boulder CO 80307-3659, USA
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Switchboard +1 303 499 1701 • Customer Support Toll Free +1 800 408 9457 • Fax +1 303 262 4058

VAISALA

TECHNICAL DATA DSC111 (Spectro)

ELECTRICAL

Power supply	9 ... 30 VDC
Power consumption for operation	0,7 W above 5°C max 1.9 W below 5°C
Power consumption for lens heaters	0 ... 4 W user adjustable
Interfaces	RS-485 isolated, RS-232
Connectors	3 x M12 (5 pins)
1:	RS-485 and power, male
2:	RS-232, male
3:	RS-485 and power, female Extension connector for the DST111
Cables	3 m, 10 m, 25 m One end without connector 0,6 m extension cable to the DST111

ENVIRONMENTAL

Operating temperature	-40°C/°F...+60°C/140°F
Operating humidity	0 ... 100 % RH
CE Compliant	IEC(EN)-61326
Safety	Eye-safe, Laser class 1
Vibration	IEC 60721-3-3

INSTALLATION

Measuring distance	6 ... 50 ft
Measuring area	Diam. 10" at 30ft
Installation angle from the horizontal line	30 ... 85°
Fits onto the standard sensor arm DM32ARM with cross-section of 40 mm x 40 mm	

MEASURING RANGE

Layer thickness*	
Water	0.00 ... 2 mm
Ice	0.00 ... 2 mm
Snow	0.00 ... 20 mm
Resolution	0.01 mm
Friction coefficient	0.01 ... 1.00
Resolution	0.01 units
Surface states	Dry, Moist, Wet, Snow/Frost, Ice, Slush

MECHANICAL

Dimensions (cm)	46 x 21 x 14
Weight	7 lb / 3.7 kg

**Units can be displayed in inches*

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VAISALA

Vaisala Non-Invasive Pavement Surface Temperature Sensor DST111 (Cyclo)

Features and Benefits

- Non-invasive remote temperature measurement
- Unique correction of the error caused by the emissivity of the road surface, negating the need for emissivity adjustment
- Easy installation and service
- Low maintenance costs
- No internal moving parts
- Stable measurement results even with intense traffic
- Weather-proof, durable design
- Assessment of air temperature and humidity
- Easy integration with Vaisala ROSA Road Weather Station
- Capability to act as stand-alone device in remote locations with solar/gsm options
- NTCIP compliant when used in conjunction with Vaisala DMC interface card

The unique Cyclo sensor provides a non-invasive alternative to measuring pavement surface temperature. By measuring the infrared radiation emitted by the surface and applying intelligent signal processing, Cyclo provides a reliable remote surface temperature measurement.

Cyclo provides reliable results in conditions where most of the commercially available infrared sensors fail. At night time, when the road surface is cooling under a clear sky, conventional infrared sensors provide an error of up to -3°C (-7°F) due to emissivity conditions of the road surface. Cyclo compensates for this error by its unique design.

Installation of Cyclo is easy, requiring no slot cutting or closure of the road. Supplied with solar/gsm options, the sensor is ideal for stand-alone operation in remote/in-fill locations and on bridge decks (when used in conjunction with DSC111 – Spectro). The sensor is simply installed on a mast, or existing structure beside the road.

Cyclo can also be installed alongside an existing Vaisala ROSA Road Weather Station.

Together with Spectro, which measures surface state, Cyclo forms a versatile stand-alone weather station.

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VAISALA

TECHNICAL DATA **DST111 (Cyclo)**

ELECTRICAL

Power supply	9 ... 30 VDC
Power consumption	70 mW
Interface	
DST111	Isolated RS-485
DST111R	RS-232
Connector	M12 (5 pins)
DST111	RS-485 and power, male
DST111R	RS-232 and power, male
Cables	3 m, 10 m, 25 m
	One end without connector
	0.6 m extension cable to the DSC111

ENVIRONMENTAL

Operating temperature	-40°C/°F...+60°C/140°F
Operating humidity	0 ... 100 % RH
CE Compliant	IEC(EN)-61326
Vibration	IEC 60721-3-3

INSTALLATION

Measuring distance	6 ... 50ft
Measuring area	Diam. 1 Yd at 30 ft
Installation angle from the horizontal line	30 ... 85°
Fits onto the standard sensor arm DM32ARM (cross-section of 40 mm x 40 mm)	

MEASURING RANGE

Resolution	0.1 °C/°F
Surface temperature	-40°C/°F...+60°C/140°F
Time constant	1 min
Data refresh time	30 s

MECHANICAL

Dimensions (cm)	32 x 13 x 10
Weight	2lb / 1.6 kg

The accuracy and measuring range of air temperature and relative humidity can be found in the data sheet of the Vaisala Miniature Humidity and Temperature Probe HMP50. However the main purpose of this probe is to ascertain the temperature of the unit, therefore due to the location of the probe within the housing, care should be taken when using the readings of air temperature and humidity.

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Appendix B: Road Surface State Comparison

Vaisala time	Vaisala Condition	Video time	Video Condition
2/1/2007 12:05	0	2/1/2007 12:14	0
2/1/2007 12:25	0	2/1/2007 12:20	0
2/14/2007 8:37	2	2/14/2007 8:28	2
2/14/2007 8:37	2	2/14/2007 8:38	2
2/14/2007 8:57	2	2/14/2007 8:48	2
2/14/2007 8:57	2	2/14/2007 8:57	2
2/14/2007 9:17	2	2/14/2007 9:07	2
2/14/2007 9:57	2	2/14/2007 9:57	2
2/14/2007 9:57	2	2/14/2007 10:05	2
2/14/2007 11:57	1	2/14/2007 12:02	2
2/14/2007 12:57	2	2/14/2007 12:51	2
2/14/2007 16:37	2	2/14/2007 16:33	2
2/14/2007 16:37	2	2/14/2007 16:44	2
2/15/2007 8:57	2	2/15/2007 8:55	2
2/15/2007 8:57	2	2/15/2007 9:06	2
2/15/2007 9:17	2	2/15/2007 9:16	2
2/15/2007 13:17	2	2/15/2007 13:14	2
2/22/2007 6:17	0	2/22/2007 6:27	0
2/22/2007 6:17	0	2/22/2007 6:33	0
2/22/2007 6:37	0	2/22/2007 6:40	0
3/2/2007 12:16	2	3/2/2007 12:21	2
3/2/2007 15:16	2	3/2/2007 15:02	2
3/2/2007 15:16	2	3/2/2007 15:09	2
3/2/2007 15:16	2	3/2/2007 15:19	2
3/2/2007 16:56	1	3/2/2007 17:00	1
degree of agreement	0.96		

condition	
bare dry or damp	***0***
wet with obvious water layer	***1***
snow or ice	***2***

Date	Video Time	Video Condition	Vaisala Condition
Feb.1,2008	10:52:25	partial snowy/icy, track obv. Better than lane-mid	ice
	11:41:49	partial snowy/icy, track unobv. Better than lane-mid	ice
	14:37:04	partial snowy/icy, track obv. Better than lane-mid	snow
	15:08:28	partial snowy/icy, track unobv. Better than lane-mid	snow
	15:49:17	partial snowy/icy, track unobv. Better than lane-mid	snow
Feb.2,2008	8:25:49	wet snow, track obv. Better than lane-mid	ice
	9:27:38	close to wet BP,wet snow, track unobv. Better than lane-mid	moist
Feb.6,2008	9:13:28	close to wet BP, some wet snow, track unobv. Better than lane-mid	moist
	9:56:45	partial snowy/icy, track unobv. Better than lane-mid	moist
Feb.7,2008	7:16:06	partial snowy/icy, wet snow, track obv. Better than lane-mid	ice
	8:02:38	partial snowy/icy, track obv. Better than lane-mid	ice
	10:06:16	partial snowy/icy, track unobv. Better than lane-mid	slushy
	10:50:50	thin snowy/icy, track unobv. Better than lane-mid	moist

Appendix C: Grip Level and Friction Measurements

Date	Friction Measure Time	Friction Measured	Measured Friction Mean (50m)	Measured Friction Mean (100m)	Measured Friction Mean (500m)	Measured Friction Mean (1000m)	Closest Vaisala Time	Vaisala Grip	Hourly Average Grip
	8:28:09	0.444	0.422	0.418	0.419	0.423	8:37:00	0.090	0.093
	8:38:33	0.164	0.181	0.166	0.188	0.174	8:37:00	0.090	0.093
	8:57:08	0.417	0.381	0.397	0.437	0.431	8:57:00	0.100	0.093
	9:57:51	0.314	0.357	0.390	0.392	0.378	9:57:00	0.100	0.105
	16:33:58	0.378	0.344	0.335	0.245	0.308	16:37:00	0.100	0.110
Feb.142007	16:44:35	0.324	0.325	0.342	0.405	0.408	16:37:00	0.100	0.110
	6:22:32	0.902	0.896	0.920	0.959	0.960	6:17:00	0.700	0.710
	8:55:32	0.401	0.453	0.485	0.695	0.714	8:57:00	0.090	0.310
	9:06:41	0.500	0.397	0.388	0.579	0.665	8:57:00	0.090	0.150
	9:15:59	0.374	0.356	0.329	0.636	0.754	9:17:00	0.100	0.150
Feb.152007	13:14:23	0.917	0.862	0.854	0.737	0.738	13:17:00	0.090	0.090
	12:21:45	0.145	0.141	0.151	0.140	0.139	12:16:00	0.090	0.090
	15:01:59	0.286	0.337	0.344	0.356	0.330	15:16:00	0.190	0.130
	15:09:14	0.314	0.292	0.271	0.283	0.265	15:09:00	0.190	0.130
	15:19:20	0.347	0.345	0.333	0.381	0.359	15:19:00	0.190	0.130
Mar.22007	17:00:52	0.948	1.005	0.995	0.969	0.978	16:56:00	0.780	0.780

Linear Regression Model 1: Hourly Average Grip to Spot-Wise Measured Friction

Regression Statistics	
Multiple R	0.915929
R Square	0.838926
Adjusted R Square	0.826536
Standard Error	0.092978
Observations	15

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.585331	0.5853312	67.70825	1.64E-06
Residual	13	0.112384	0.0086449		
Total	14	0.697715			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*

Intercept	-0.16416	0.051664	-3.177551	0.007275	-0.275776	-0.05255	-0.2758	-0.053
Friction Measured	0.902228	0.109647	8.2285021	1.64E-06	0.66535	1.139105	0.66535	1.1391

Linear Regression Model 2: Hourly Average Grip to 50m Mean Measured Friction

Regression Statistics	
Multiple R	0.963738
R Square	0.928791
Adjusted R Square	0.922857
Standard Error	0.063638
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.633876	0.6338764	156.5192	3.04E-08
Residual	12	0.048598	0.0040498		
Total	13	0.682474			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.15881	0.034784	-4.565735	0.000648	-0.234599	-0.08303	-0.2346	-0.083
0.4222	0.914409	0.07309	12.510762	3.04E-08	0.75516	1.073658	0.75516	1.0737

Linear Regression Model 3: Hourly Average Grip to 100m Mean Measured Friction

Regression Statistics	
Multiple R	0.960027
R Square	0.921651
Adjusted R Square	0.915122
Standard Error	0.066753

Observations	14

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.629003	0.6290032	141.1608	5.4E-08
Residual	12	0.053471	0.0044559		
Total	13	0.682474			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.15383	0.036227	-4.24614	0.001135	-0.23276	-0.07489	-0.2328	-0.075
0.418	0.897201	0.075515	11.881111	5.4E-08	0.732668	1.061734	0.73267	1.0617

Linear Regression Model 4: Hourly Average Grip to 500m Mean Measured Friction

Regression Statistics	
Multiple R	0.873816
R Square	0.763554
Adjusted R Square	0.74385
Standard Error	0.115963
Observations	14

ANOVA

	df	SS	MS	F	Significance F
Regression	1	0.521106	0.5211061	38.75158	4.42E-05
Residual	12	0.161368	0.0134474		
Total	13	0.682474			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.14457	0.066371	-2.178209	0.050054	-0.289182	4.01E-05	-0.2892	4E-05
0.4188	0.767557	0.123301	6.2250765	4.42E-05	0.498907	1.036206	0.49891	1.0362

Linear Regression Model 5: Hourly Average Grip to 1000m Mean Measured Friction

Regression Statistics	
Multiple R	0.824113
R Square	0.679162

Adjusted R Square	0.652426
Standard Error	0.135081
Observations	14

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.463511	0.4635108	25.40208	0.000289
Residual	12	0.218964	0.018247		
Total	13	0.682474			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.11584	0.075923	-1.52578	0.15298	-0.281265	0.04958	-0.2813	0.0496
0.4233	0.686676	0.136244	5.0400474	0.000289	0.389826	0.983526	0.38983	0.9835

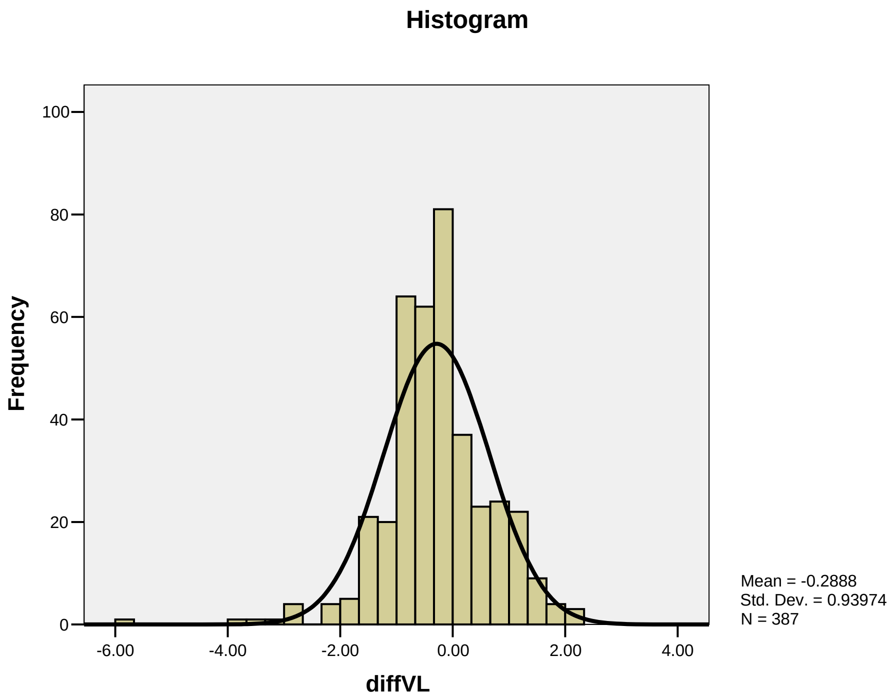
Date	Friction Measure Time	Friction Measured	Measured Friction Mean (50m)	Measured Friction Mean (100m)	Measured Friction Mean (500m)	Measured Friction Mean (1000m)	Closest Vaisala Time	Vaisala Grip	Hourly Average Grip
	10:52:25	0.453	0.458	0.464	0.399	0.441	11:00:00	0.090	0.090
	11:41:49	0.081	0.085	0.079	0.106	0.120	11:40:00	0.090	0.090
	14:37:04	0.407	0.473	0.527	0.506	0.551	14:40:00	0.090	0.090
	15:08:28	0.476	0.429	0.405	0.336	0.381	15:00:00	0.090	0.090
Feb.1,2008	15:49:17	0.226	0.239	0.253	0.263	0.299	15:40:00	0.090	0.100
	8:25:49	0.746	0.765	0.714	0.516	0.519	8:20:00	0.100	0.120
Feb.2,2008	9:27:38	0.647	0.591	0.611	0.758	0.781	9:20:00	0.820	0.820
	9:13:28	0.760	0.777	0.775	0.764	0.746	9:18:00	0.290	0.277
Feb.6,2008	9:56:45	0.770	0.798	0.796	0.791	0.783	9:58:00	0.820	0.680
	7:16:06	0.406	0.454	0.504	0.450	0.463	7:18:00	0.100	0.103
	8:02:38	0.612	0.606	0.608	0.551	0.575	7:58:00	0.100	0.103
	10:06:16	0.684	0.753	0.715	0.687	0.665	9:58:00	0.710	0.540
Feb.7,2008	10:50:50	0.853	0.803	0.789	0.751	0.742	10:58:00	0.820	0.783

Appendix D: Temperature Reading Difference Statistics

December, 2006

Temperature Reading Difference (Vaisala – Lufft)

N	Valid	387
	Missing	0
Mean		-.2888
Std. Error of Mean		.04777
Median		-.3000
Mode		-.70
Std. Deviation		.93974
Variance		.883
Skewness		-.649
Std. Error of Skewness		.124
Kurtosis		3.599
Std. Error of Kurtosis		.247
Range		7.97
Minimum		-5.83
Maximum		2.13
Sum		-111.75
Percentiles	25	-.7667
	50	-.3000
	75	.2000



One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
diffVL	-6.045	386	.000	-.28876	-.3827	-.1948

January, 2007

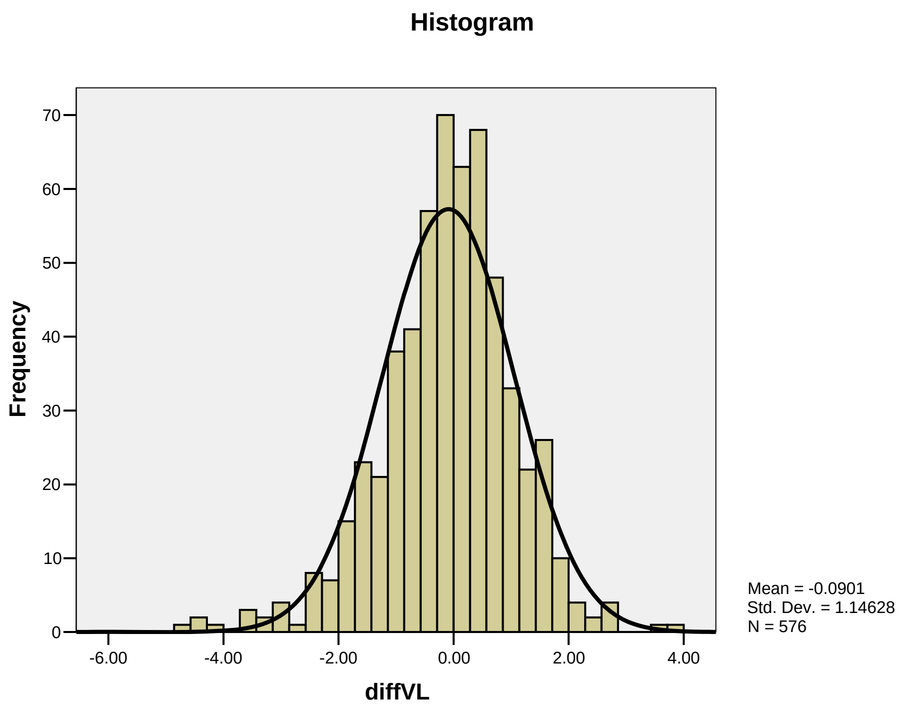
Temperature Reading Difference (Vaisala – Lufft)

N	Valid	733
	Missing	0
Mean		.5909
Std. Error of Mean		.05221
Median		.3389(a)
Mode		-.27(b)
Std. Deviation		1.41353
Variance		1.998
Skewness		.264
Std. Error of Skewness		.090
Kurtosis		-.690
Std. Error of Kurtosis		.180
Range		7.73
Minimum		-3.53
Maximum		4.20
Sum		433.16
Percentiles	10	-1.1000(c)
	20	-.6667
	25	-.5000
	30	-.3333
	40	-.1000
	50	.3389
	60	.9433
	70	1.4767
	75	1.7333
	80	1.9656
	90	2.5667

a Calculated from grouped data.

b Multiple modes exist. The smallest value is shown

c Percentiles are calculated from grouped data.



One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
diffVL	-1.887	575	.060	-.09011	-.1839	.0037

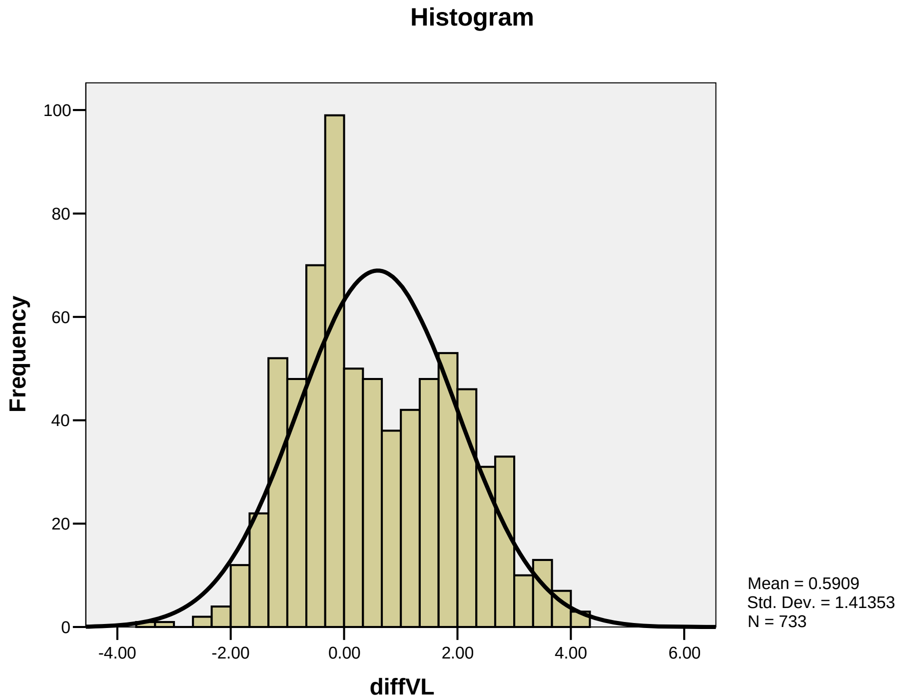
February, 2007

Temperature Reading Difference (Vaisala – Lufft)

N	Valid	576
	Missing	0
Mean		-.0901
Std. Error of Mean		.04776
Median		-.0333(a)
Mode		.60
Std. Deviation		1.14628
Variance		1.314
Skewness		-.513
Std. Error of Skewness		.102
Kurtosis		1.459
Std. Error of Kurtosis		.203
Range		8.52
Minimum		-4.75
Maximum		3.77
Sum		-51.91
Percentiles	10	-1.5300(b)
	20	-.9311
	25	-.7354
	30	-.5667
	40	-.2667
	50	-.0333
	60	.2589
	70	.4667
	75	.6000
	80	.8000
	90	1.3283

a Calculated from grouped data.

b Percentiles are calculated from grouped data.



One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
diffVL	-1.887	575	.060	-.09011	-.1839	.0037

March, 2007

Temperature Reading Difference (Vaisala – Lufft)

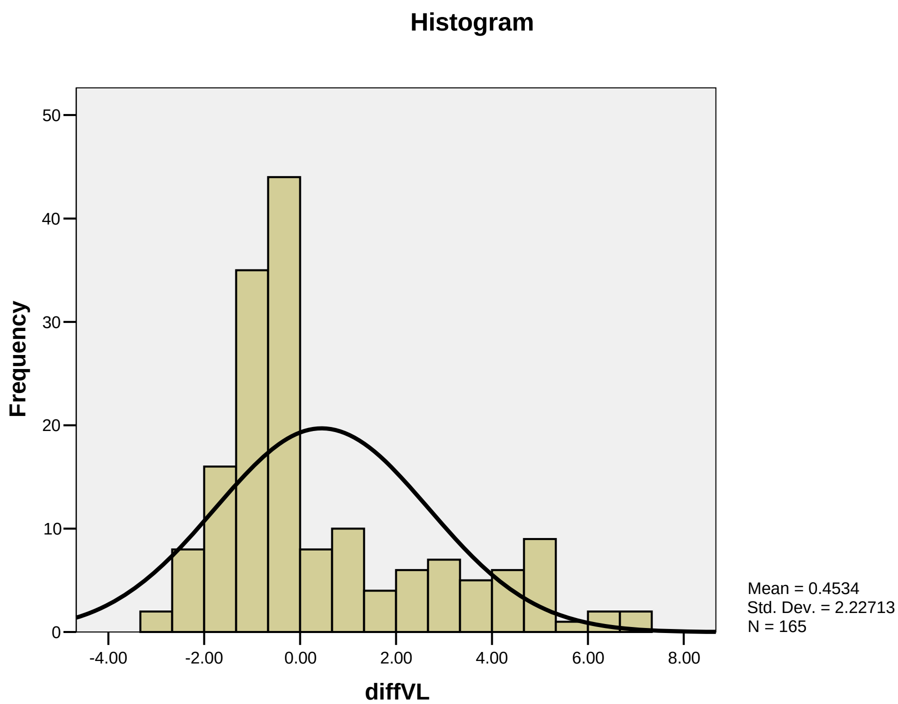
Statistics

diffVL

N	Valid	165
	Missing	0
Mean		.4534
Std. Error of Mean		.17338
Median		-.3667(a)
Mode		-.43
Std. Deviation		2.22713
Variance		4.960
Skewness		1.121
Std. Error of Skewness		.189
Kurtosis		.368
Std. Error of Kurtosis		.376
Range		10.10
Minimum		-3.00
Maximum		7.10
Sum		74.81
Percentiles	10	-1.6600(b)
	20	-1.1417
	25	-1.0063
	30	-.8667
	40	-.5833
	50	-.3667
	60	-.1422
	70	.8667
	75	1.6333
	80	2.6000
	90	4.3333

a Calculated from grouped data.

b Percentiles are calculated from grouped data.



One-Sample Test

	Test Value = 0					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
diffVL	2.615	164	.010	.45340	.1111	.7958

Appendix E: Temperature Reading Difference Statistics by Temperature Ranges

Dec. 2006 – Mar. 2007

T interval	N	Mean	Std	t	p	95%LB	95%UB	Median	Range	Min	Max
[-20,-15)	104	2.231	0.654	34.801	0	2.104	2.359	2.283	3.73	0.6	4.33
[-15,-10)	346	1.053	0.902	21.713	0	0.958	1.149	1.100	7.17	-1.8	5.37
[-10,-5)	411	0.407	1.138	7.243	0	0.296	0.517	0.300	9.33	-2.23	7.1
[-5,0)	472	-0.288	0.980	-6.381	0	-0.376	-0.199	-0.267	10.19	-5.83	4.36
[0,5)	338	-0.756	0.800	-17.373	0	-0.841	-0.670	-0.700	8.02	-4.75	3.27
[5,10)	137	-1.271	0.832	-17.877	0	-1.411	-1.130	-1.267	5.31	-4.53	0.78
[10,15)	8	-2.088	1.496	-3.947	0	-3.338	-0.837	-1.738	4.63	-4.13	0.5

Monthly Breakdown

statistics of difference by month												
Month	T interval	N	Mean	Std	t	p	95%LB	95%UB	Median	Range	Min	Max
	[-15,-10)	23	0.94	0.86	5.27	0.00	0.57	1.32	0.87	3.03	-0.9	2.13
	[-10,-5)	57	0.85	0.42	15.4	0.00	0.74	0.96	0.90	1.78	-0.38	1.4
	[-5,0)	117	-0.42	1.04	-4.3	0.00	-0.61	-0.23	-1.17	7.17	-5.83	1.33
	[0,5)	147	-0.64	0.43	-18	0.00	-0.71	-0.57	-0.63	3.1	-2.7	0.4
	[5,10)	40	-0.87	0.62	-8.8	0.00	-1.07	-0.67	0.92	2.33	-2	0.33
Dec.2006	[10,15)	3	-1.48							0.34	-1.68	-1.33
	[-20,-15)	84	2.26	0.55	37.9	0.00	2.14	2.38	2.32	2.28	1.18	3.47
	[-15,-10)	133	1.56	0.69	26.2	0.00	1.45	1.68	1.67	3.6	-0.63	2.97
	[-10,-5)	113	0.77	0.79	10.4	0.00	0.63	0.92	0.77	4.27	-1.23	3.03
	[-5,0)	182	-0.04	0.78	-0.6	0.53	-0.15	0.08	-0.17	5.77	-2.17	3.6
	[0,5)	120	-0.53	0.74	-7.9	0.00	-0.67	-0.40	-0.61	5.07	-1.8	3.27
	[5,10)	66	-1.24	0.59	-17	0.00	-1.39	-1.09	-1.27	3.28	-2.5	0.78
Jan.2007	[10,15)	3	-2.88	0.94					-3.30	1.73	-3.53	-1.8
	[-20,-15)	9	1.25	0.37	10.2	0.00	0.97	1.53	1.33	1.1	0.6	1.7
	[-15,-10)	174	0.63	0.73	11.3	0.00	0.52	0.74	0.55	4.5	-1.8	2.7
	[-10,-5)	209	-0.04	0.87	-0.6	0.00	-0.15	0.08	-0.03	5.99	-2.23	3.77
	[-5,0)	115	-0.45	0.98	-5	0.00	-0.64	-0.27	-0.50	5.87	-3.03	2.83
	[0,5)	52	-1.38	1.23	-8.1	0.00	-1.73	-1.04	-1.38	6.42	-4.75	1.67
	[5,10)	16	-2.26	1.16	-7.8	0.00	-2.88	-1.64	-1.86	3.93	-4.53	-0.6
Feb.2007	[10,15)	1	-4.13									
	[-20,-15)	11	2.84	0.74	12.7	0.00	2.34	3.33	2.73	2.7	1.63	4.33
	[-15,-10)	16	1.60	1.59	4.02	0.00	0.75	2.45	1.06	5.8	-0.43	5.37
	[-10,-5)	32	1.21	2.58	2.66	0.01	0.28	2.14	-0.13	8.05	-0.95	7.1
	[-5,0)	58	-0.49	1.25	-3	0.00	-0.81	-0.16	-0.74	6.39	-2.03	4.36
	[0,5)	19	-1.34	0.75	-7.8	0.00	-1.70	-0.98	-1.43	2.83	-2.8	0.03
	[5,10)	15	-1.42	0.98	-5.6	0.00	-1.97	-0.88	-1.48	3.5	-3	0.5
Mar.2007	[10,15)	1	0.50									