ITS Professional Capacity Building Program

T3e Webinar

Smart Sensors and Infrasructures for Transportation
July 29, 2021

Roadway Ice/snow Detection using a Novel Infrared Thermography Technology

Presenter: Keping Zhang

Infrastructure Sensing & Experimental Mechanics (iSEM) Lab

Department of Civil & Environmental Engineering, University of Utah

In collaboration with Prof. Yang of UTRAIL at the University of Utah

Infrastructure Sensing & Experimental Mechanics Lab

UTAH TRANSPORTATION & ARTIFICIAL INTELLIGENCE LAB

THE UNIVERSITY OF UTAH®

Outline

1. Introduction
   - Background
   - Current Technologies
   - Proposed Solution

2. Polarized Infrared Thermography Development
   - Strategy 1 - Filter out S-polarized reflections at certain favorable perspective angle
   - Strategy 2 - Reconstruct IR images with P- & S-polarized measurements
   - Lab Tests

3. Conclusions & Ongoing Work

1. Introduction	Background

Slippery road condition during winter seasons imposes threats to traffic safety in snowy regions (70% of U.S. roads & population [1]).

Coefficient of friction for rubber tire on slippery road surface [2]

Tire on	Coefficient of friction
Snow	0.5
Compact snow	0.4
Ice	0.15

This will
- reduce tire friction
- lengthen vehicle braking distance
- induce risks on car crashing

Black ice on road surface

FHWA safety data [1] reports
- average of 1,300 deaths
- average of 116,800 injuries

per year due to snowy and icy roads

Takeaway: it is important to evaluate slippery road conditions & evaluate traffic safety.

[1] USDOT FHWA Road Weather Management Program website https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm
[2] Strong, C. K., Ye, Z., Shi, X. (2010). Safety effects of winter weather: the state of knowledge and remaining challenges. *Transport reviews*, 30(6), 677-699.

THE UNIVERSITY OF UTAH®

1. Introduction | Current Technologies

Summary of past work on roadway ice/snow detection

Item #	Phenomena/Technique	Investigators/ Relevant publication
1	RWIS	Aurora 2005* [3]
2	Infrared thermometer	Vaisala DST111[4], Ye et al.[5], Jonsson et al. [6]
3	Passive infrared thermography with radiation polarization	Reed & Barbour [7]
4	Active infrared radiation backscatter	Vaisala DSC111[4], Misener [8], Joshi [9]
5	Video camera	AerotechTelub* [10], Saito et al.*[11]
6	Laser light polarization	Schmokel [12]
7	Microwave reflection	Kubichek &Yoakum-Stover [13]
8	Car reactions on slippery surfaces: acceleration, ABS wheel speed, etc.	Robinson & Cook [14], Castillo Aguilar et al. [15]
9	Pavement temperature sensors	Albrecht*[16], SRF Consulting Group Inc.*[17]

Important attributes for each technology in roadway ice/snow detection

Attribute	Item #								
	1	2	3	4	5	6	7	8	9
Direct surface measurement	N	Y	Y	Y	Y	Y	Y	X	Y
Multi-lane coverage	N	N	Y	N	Y	Y	Y	X	N
Robustness against noise	N/A	Y	N/A	N	N	N/A	N	N/A	N/A
Distinguish snow and ice surfaces	N	N	Y	Y	N	N	N/A	N	N
Economics	N/A	Y	N	Y	Y	N/A	N/A	Y	N/A

Y: Positive; N: Negative;
N/A: Not available

Takeaway: none of current technologies satisfy all the identified attributes.

1. Introduction | Current Technologies

- Technology adopted by state DOTs

DST 111 Remote Surface Temperature Sensor: single point infrared temperature measurement, compensated by emissivity of road surface
DSC 111 Remote Surface State Sensor: single point laser spectroscopic measurement, reporting the amounts of water and ice

Spatial resolution
- DST 111: diameter of measuring area at 10 m (33 ft) 150 cm (59.1 in)
- DSC 111: diameter of measuring area at 10 m (33 ft) 20 cm (7.87 in)

Calibration: Twice per year
Cost:

Pos	Description	Quantity	Unit Price	Total Price USD
1	DST111 Temperature Sensor Remote	1 EA	4,586.00	**4,586.00**
2	DSC111 Road State Sensor Remote	1 EA	12,651.00	**12,651.00**
	Subtotal (Selling Price)			17,237.00
	Freight			10.00
Tax Due	TAX 0%			0.00
Tax Due	TAX 0%			0.00
Tax Due	TAX 0%			0.00
	Grand Total		**USD**	**17,247.00**

Takeaway: robust multi-lane measurement, less frequent calibration, less cost are desirable.

THE UNIVERSITY OF UTAH®

1. Introduction | Proposed Solution

- **Infrared Camera for multi-lane temperature measurement**

Spatial resolution:

Detector Size	Number of pixels
320 x 240	76,800
160 x 120	19,200

Target Distance (Feet)	Field of View (Feet)	Pixel Size 320 x 240 (Inches)	Pixel Size 160 x 120 (Inches)
1	0.38 x 0.29	0.014 x 0.014	0.029 x 0.029
6	2.30 x 1.73	0.086 x 0.086	0.173 x .173
10	3.83 x 2.88	0.144 x 0.144	0.288 x 0.288
20	7.67 x 5.76	0.288 x 0.288	0.575 x 0.576
50	19.17 x 14.41	0.719 x 0.720	1.437 x 1.441

FLIR A325sc

AVIO R450 Pro

Calibration frequency: every year (if looking for accurate temperature)

Cost: 320 x 240 detector ~$10k FLIR A325sc, ~$15k AVIO R450 Pro

Description	MSRP
FLIR A325sc w/25° Lens, 60 Hz, 320x240, -20°C to 350°C, w/ResearchIR Max	$9,990

Lower cost models are available.

Temperature resolution: 0.025ºC - 0.1ºC

Accuracy: ±1ºC - ±2ºC

Operating temp: -15 to 50ºC

Power consumption: 4.3 watts

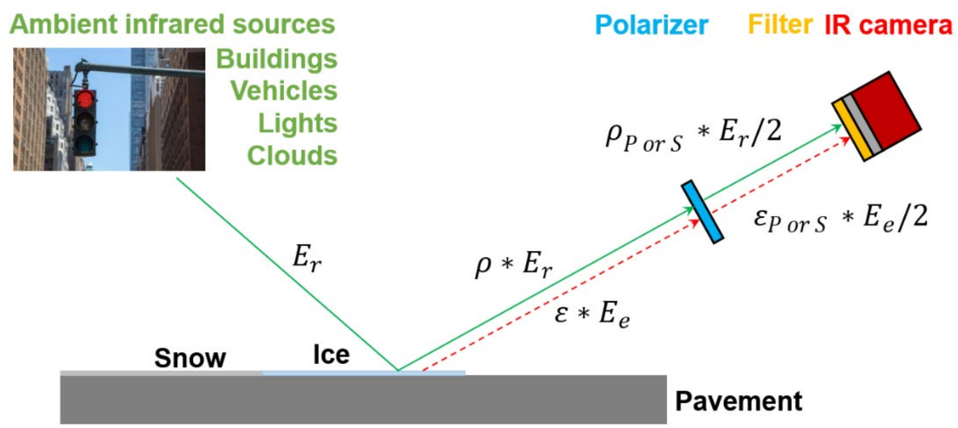
Takeaway: IR camera can provide multi-lane measurement, requires less calibration, and can be less costly.

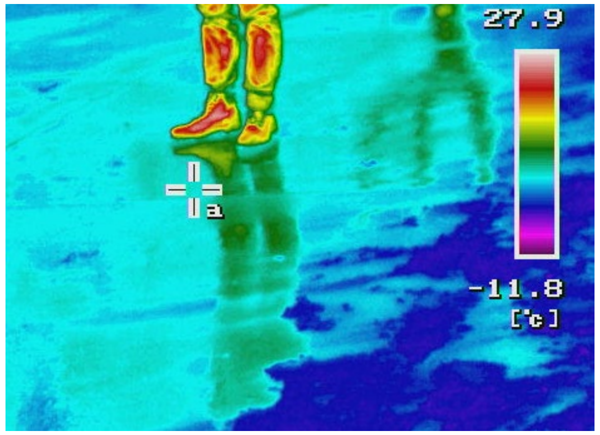
1. Introduction

Proposed Solution

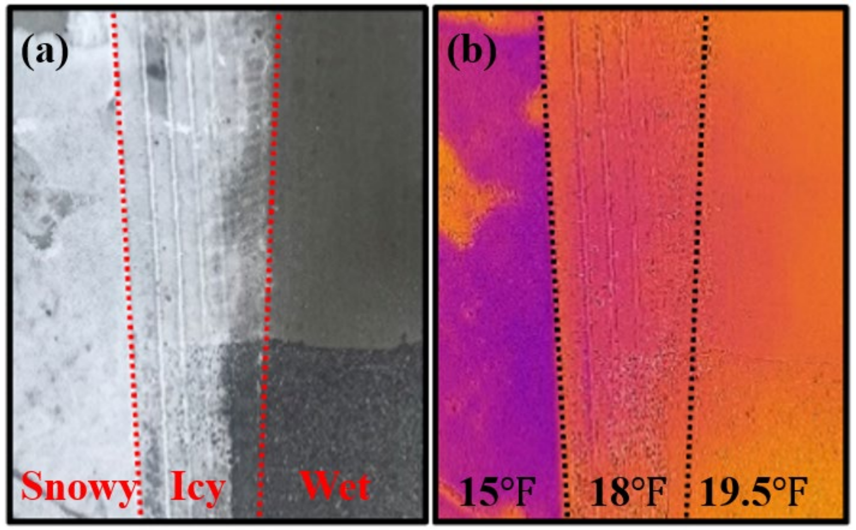
Develop a system for *multi-lane* roadway surface temperature and slippery condition evaluation exploiting tools including

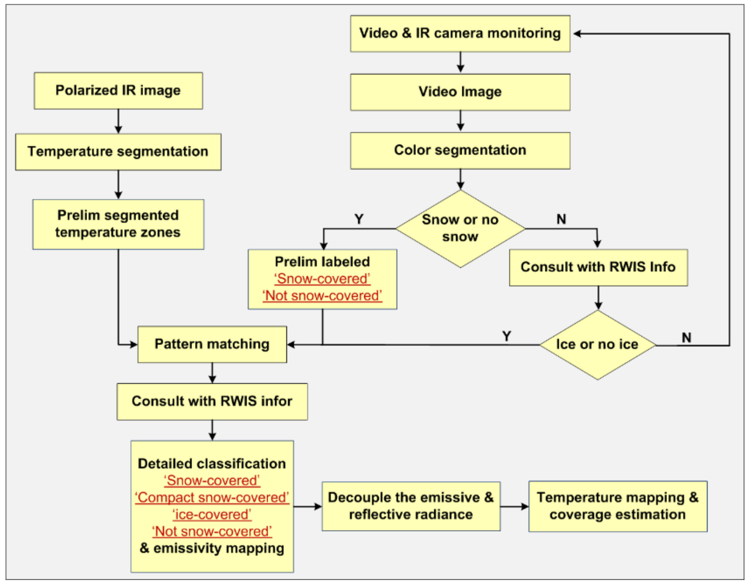
- Polarized infrared thermography (eliminating ambient thermal noises)





- Dual-sensory measurement system and algorithms (accurate temperature mapping & segmentation)

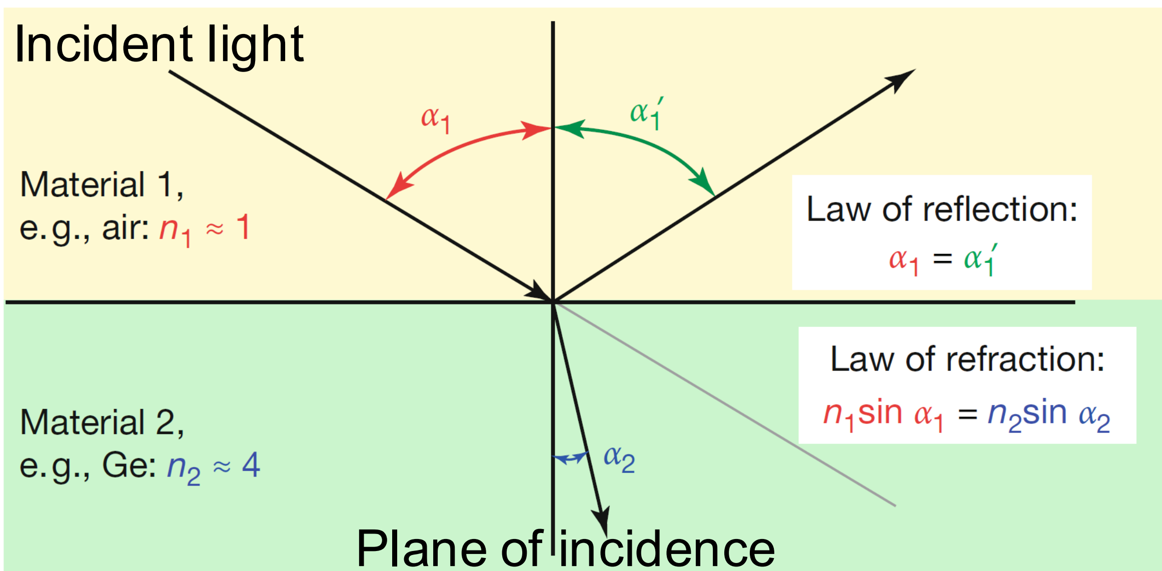




Mission – improve traffic safety during winter seasons in snowy regions by enabling *early warning of hazardous road conditions* and *facilitating snow removal performance evaluation*

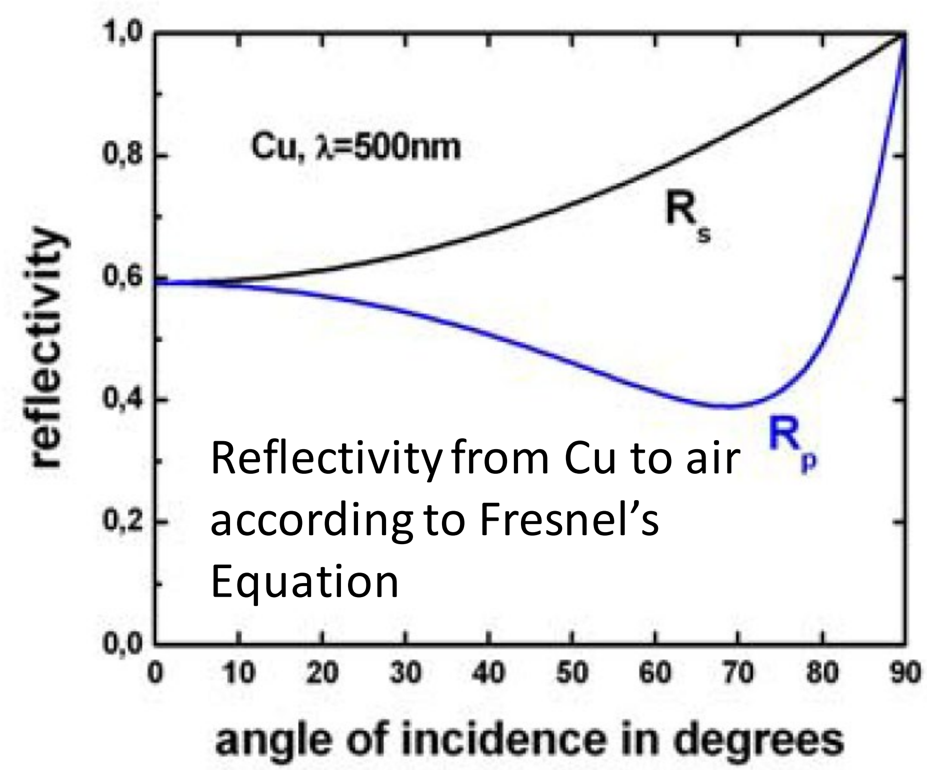
Strategy 1: Filter out S-polarized reflections at certain favorable perspective angle

Theoretical prediction of thermal reflections – Fresnel's Equation



Reflected light consisted of two contributions:

1. Light polarized parallel to plane of incidence Rp.
2. Light polarized perpendicular to plane of incidence Rs.



- Fresnel's equations

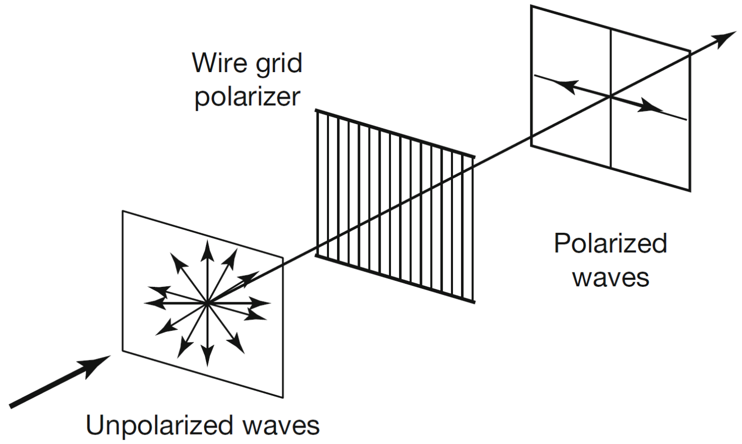
$$R_P = \left(\frac{n^2 cos\theta - \sqrt{n^2 - sin^2\theta}}{n^2 cos\theta + \sqrt{n^2 - sin^2\theta}}\right)^2$$

$$R_s = \left(\frac{cos\theta - \sqrt{n^2 - sin^2\theta}}{cos\theta + \sqrt{n^2 - sin^2\theta}}\right)^2$$

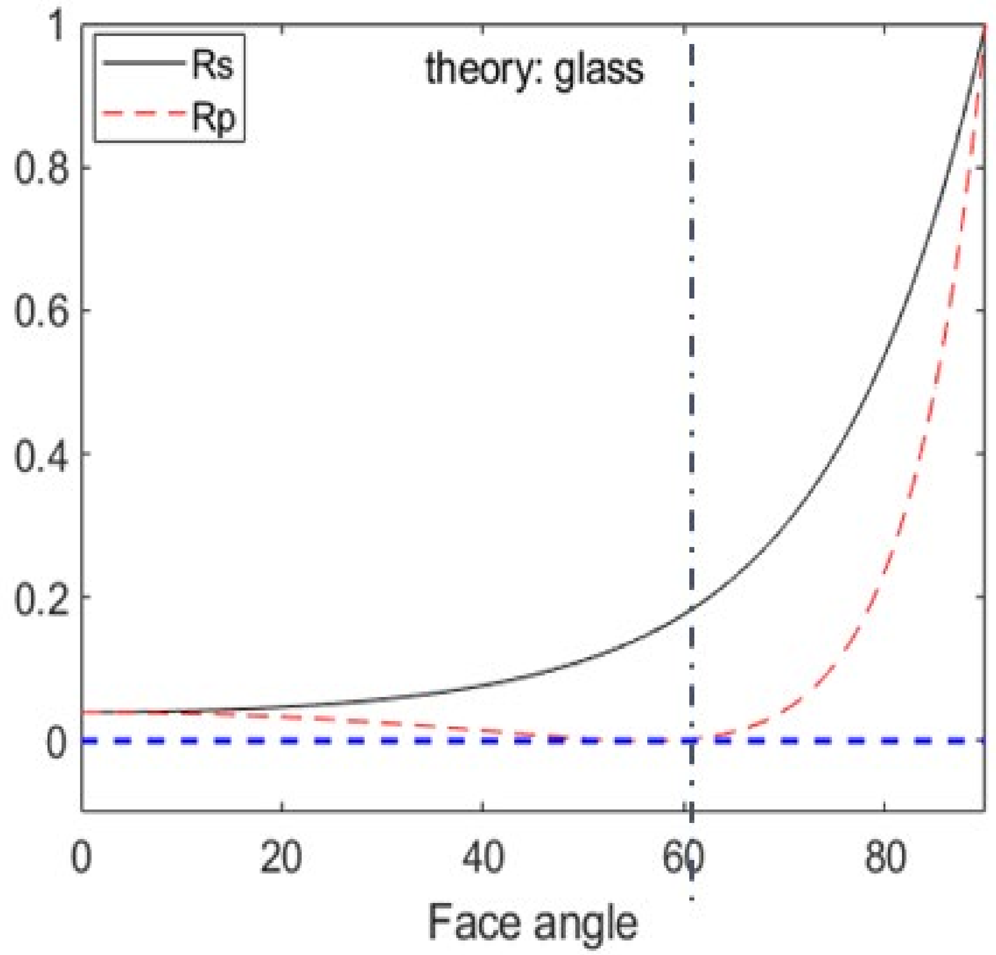
Θ: incident angle (face angle)
n: the refractivity index of the reflectivity surface

Strategy 1: Filter out S-polarized reflections at certain favorable perspective angle

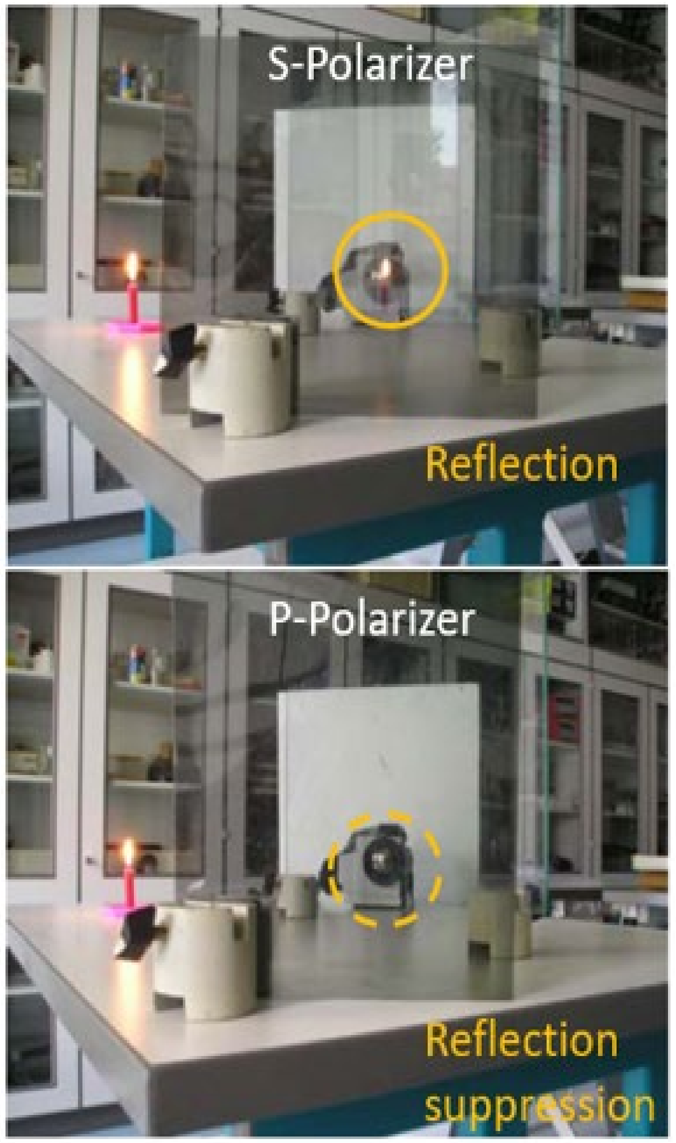
Suppression of thermal reflections using polarizer – Example



Unpolarized radiation become polarized by passing a polarizer

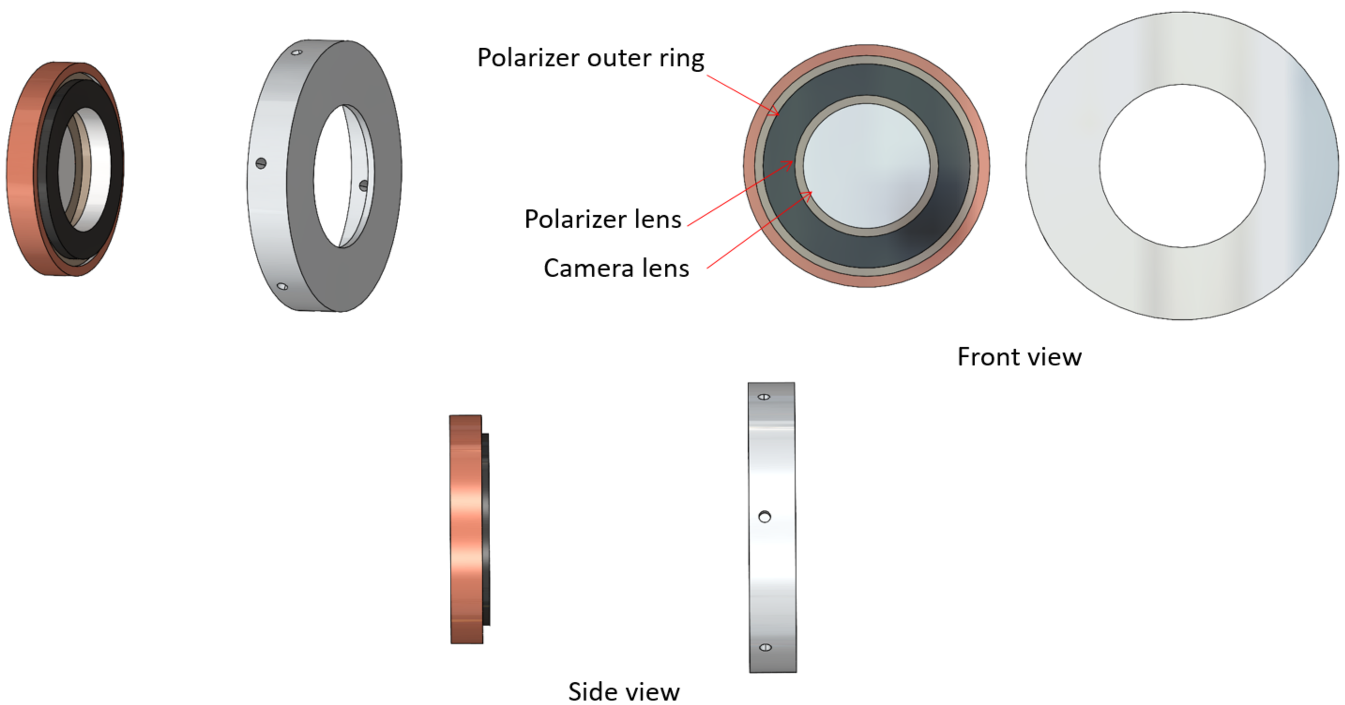


Henke, S., Karstädt, D., Möllmann, K. P., Pinno, F., & Vollmer, M. (2004)

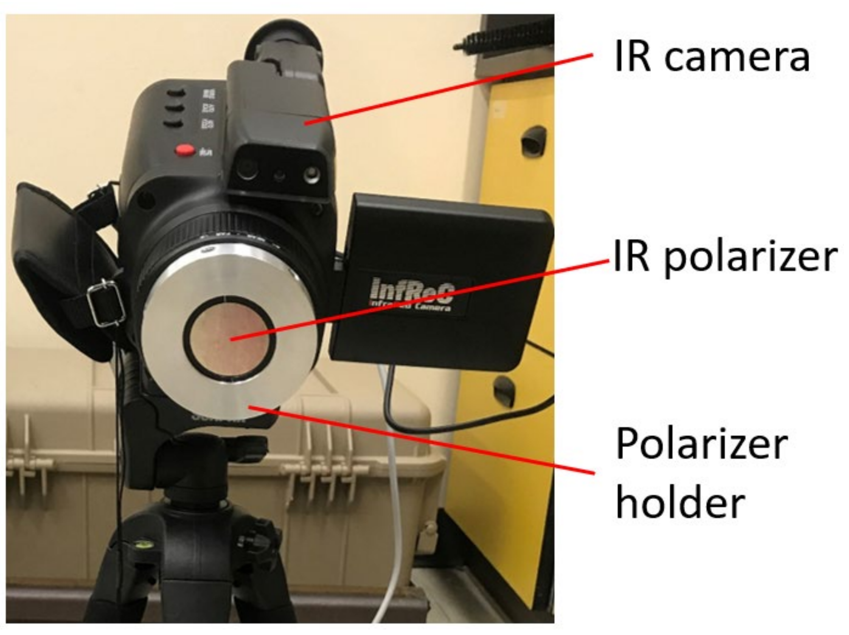


Strategy 1: Filter out S-polarized reflections at certain favorable perspective angle

Suppression of thermal reflections using polarizer – Lens-polarizer assembly design

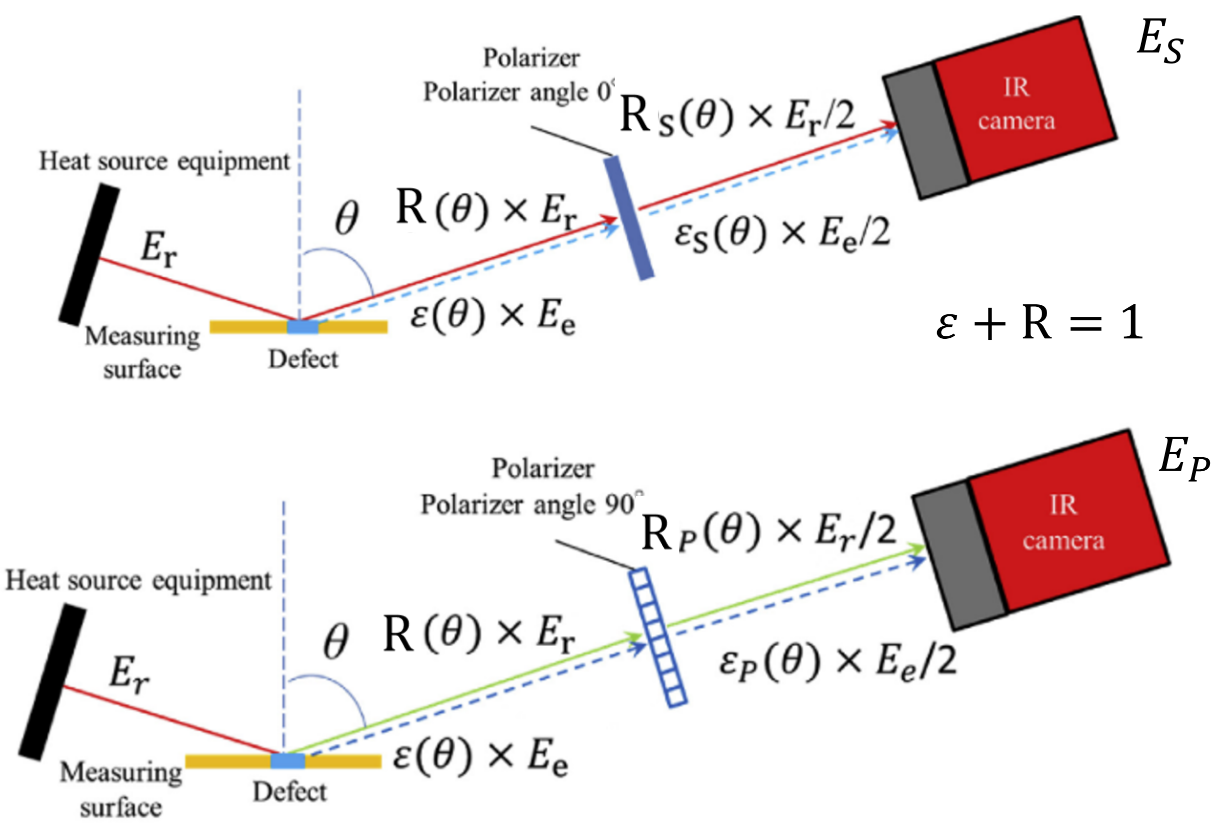


Lens-polarizer assembly



Strategy 2: Reconstruct IR images with P- & S-polarized measurements based on Kirchhoff's Law

- Re-imaging IR measurement



Separate emitted energy and reflected energy steps:

1. Take IR image at polarizer angle 0° : E_P
2. Take IR image at polarizer angle 90° : E_S
3. Quantitative separation of the energy using:

$$E_e = \frac{2(R_P E_S - R_S E_P)}{\tau(R_P \varepsilon_S - R_S \varepsilon_P)}$$

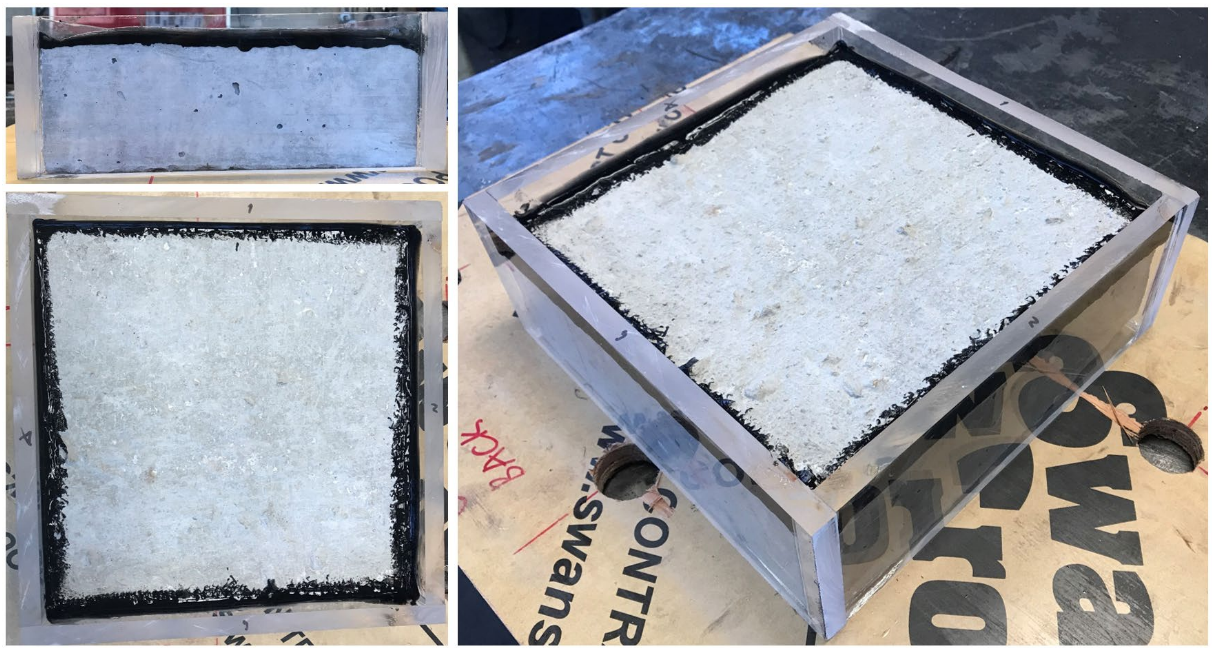
$$E_r = \frac{2(\varepsilon_P E_S - \varepsilon_S E_P)}{\tau(R_S \varepsilon_P - R_P \varepsilon_S)}$$

4. Re-imaging E_e without background reflection E_r

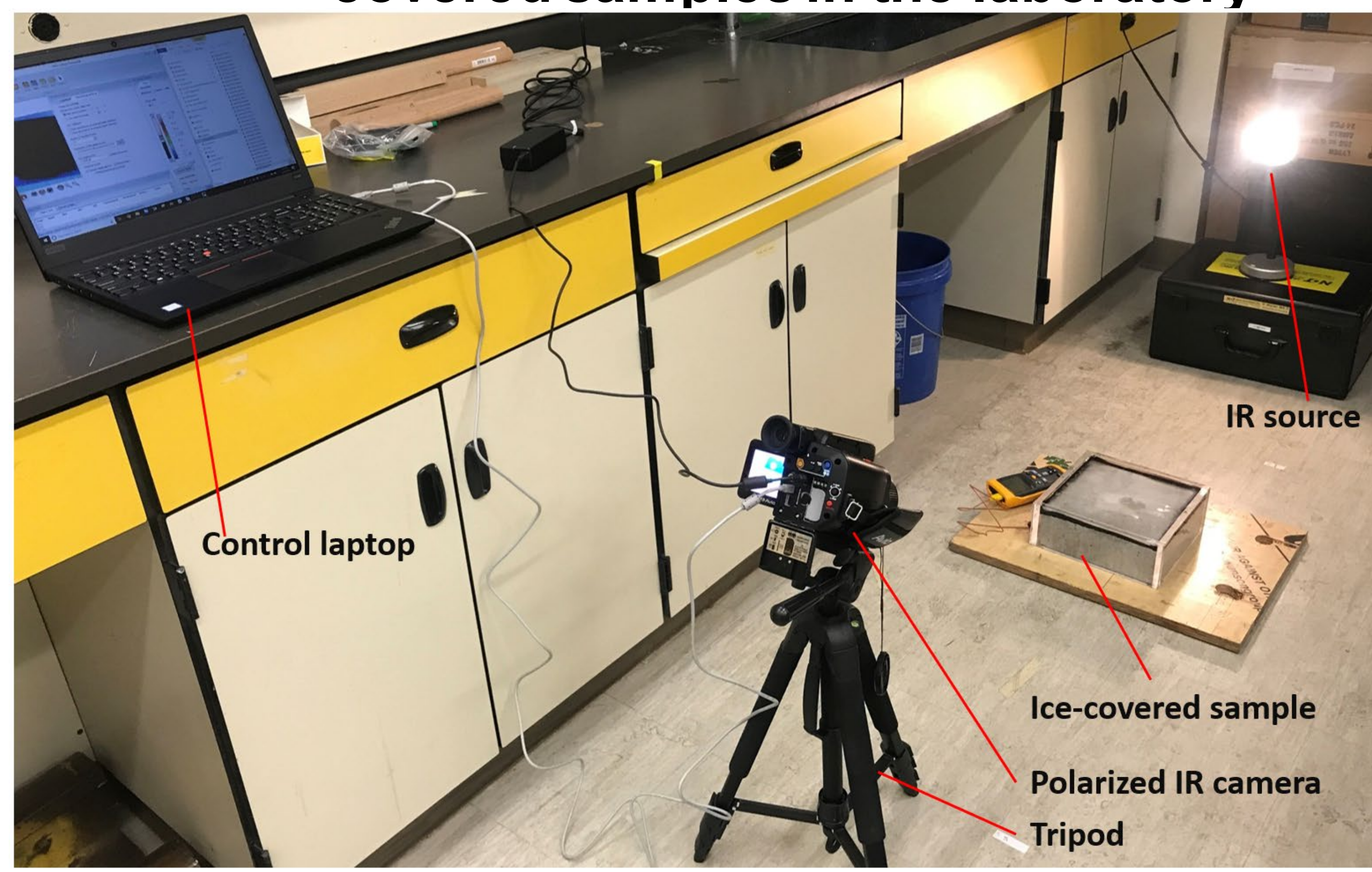
THE UNIVERSITY OF UTAH®

2. Polarized infrared thermography development | Lab tests

Sample preparation (dry, wet, & ice-covered)

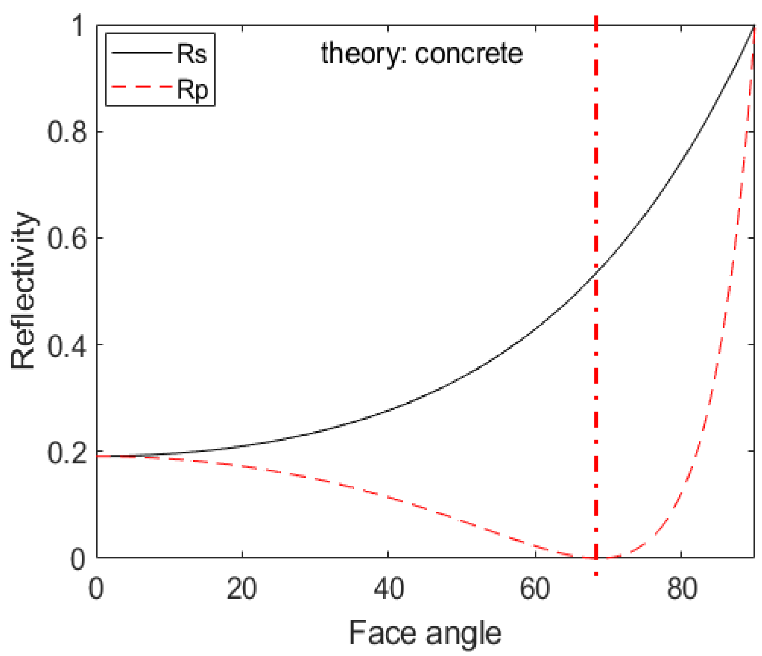


Data collection on dry, wet, & ice-covered samples in the laboratory

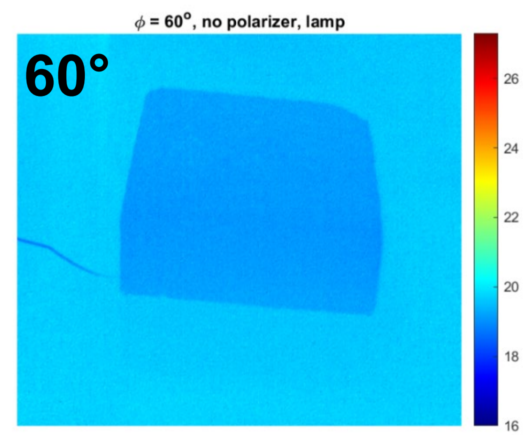


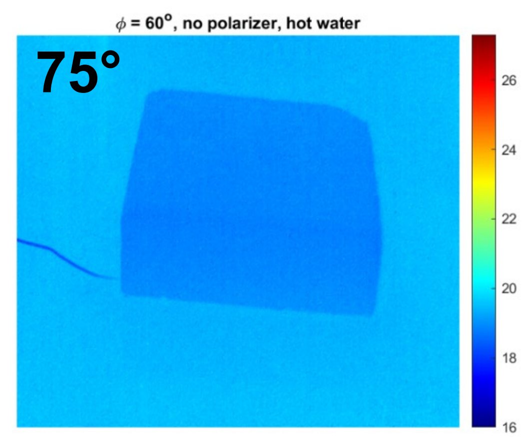
2. Polarized infrared thermography development | Lab tests

Data Analysis - dry concrete

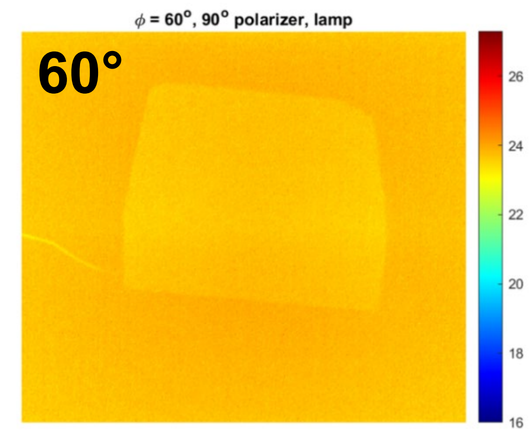


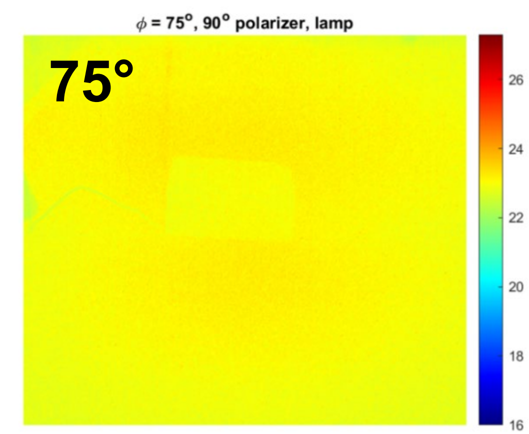
Original



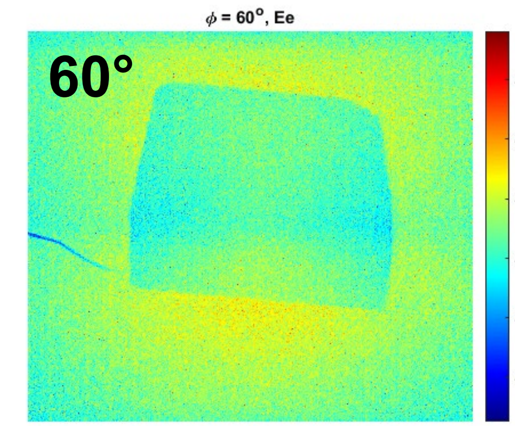


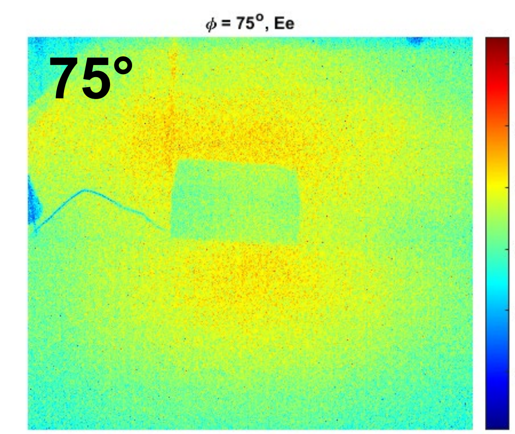
Strategy 1





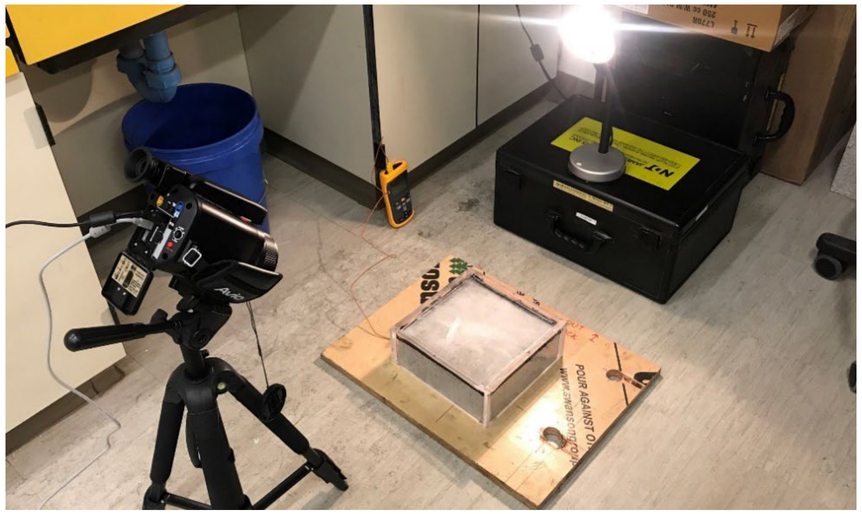
Strategy 2

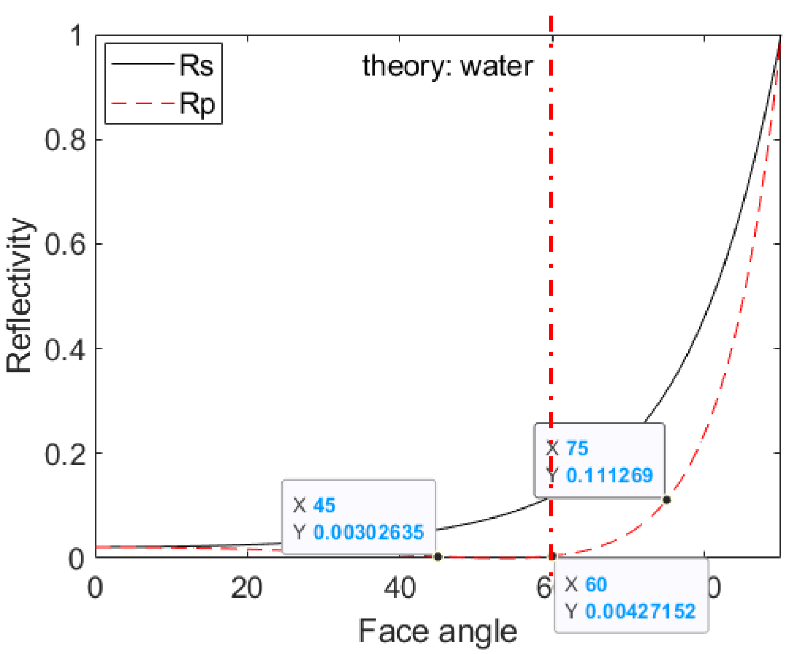




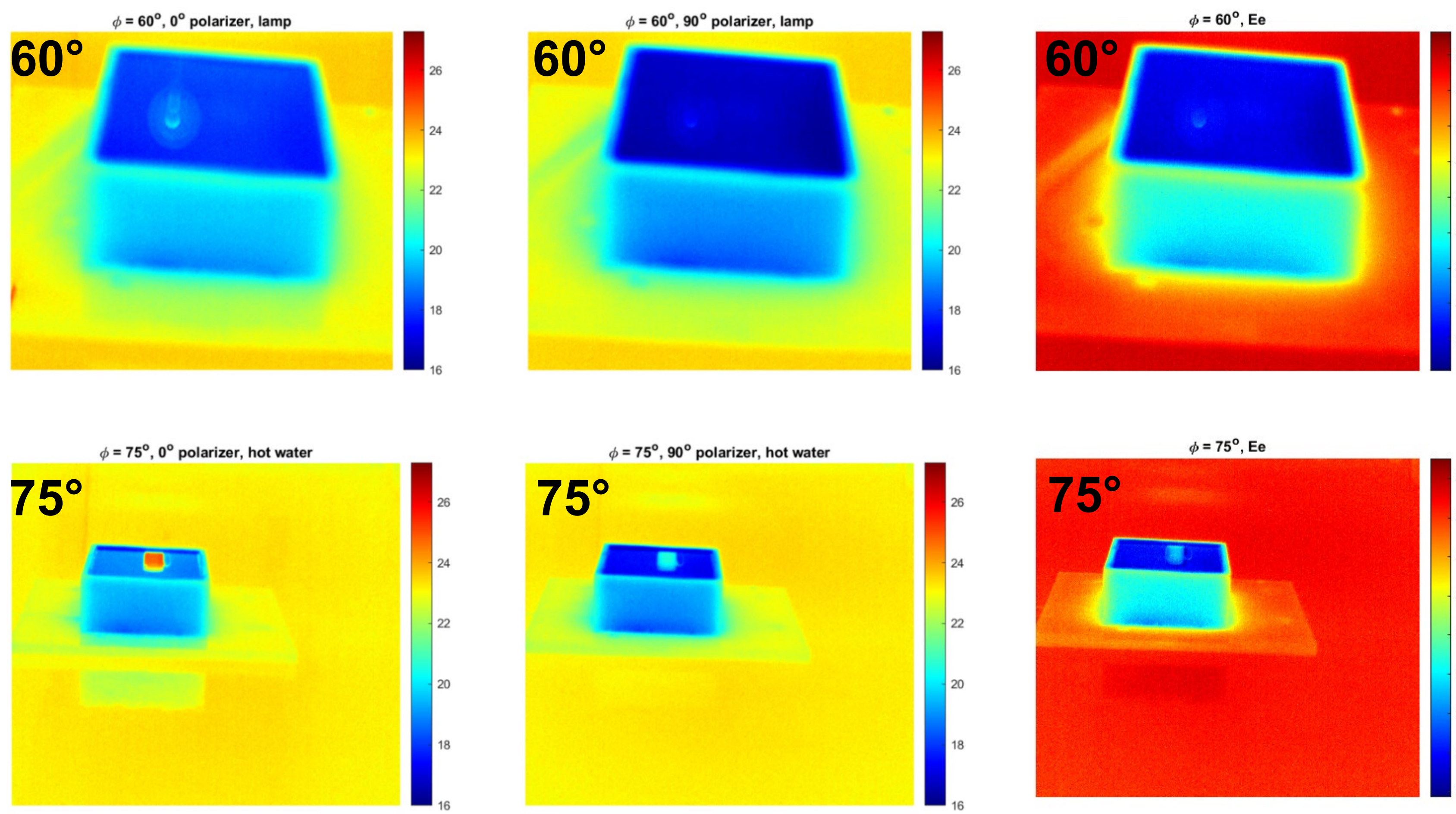
2. Polarized infrared thermography development | Lab tests

Data Analysis - wet concrete

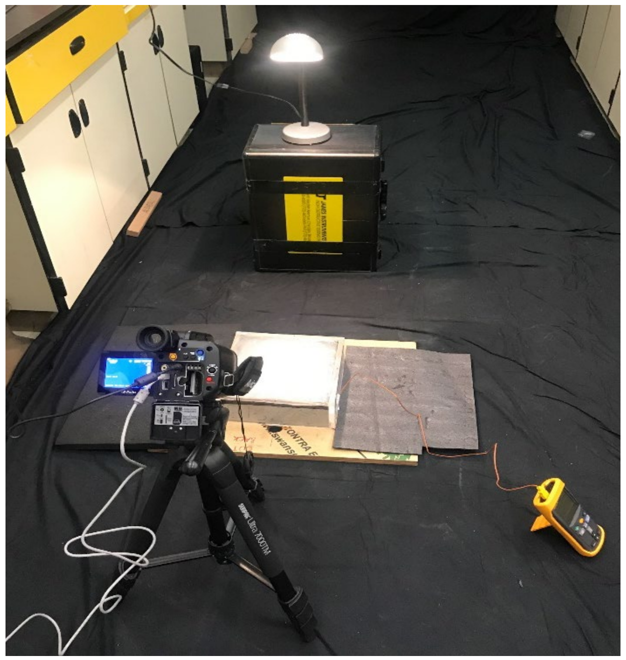


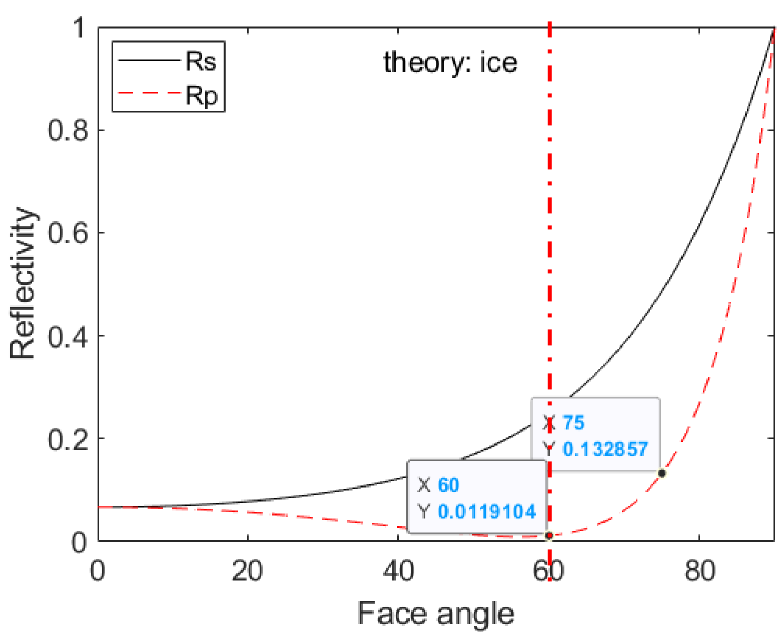


Original | Strategy 1 | Strategy 2

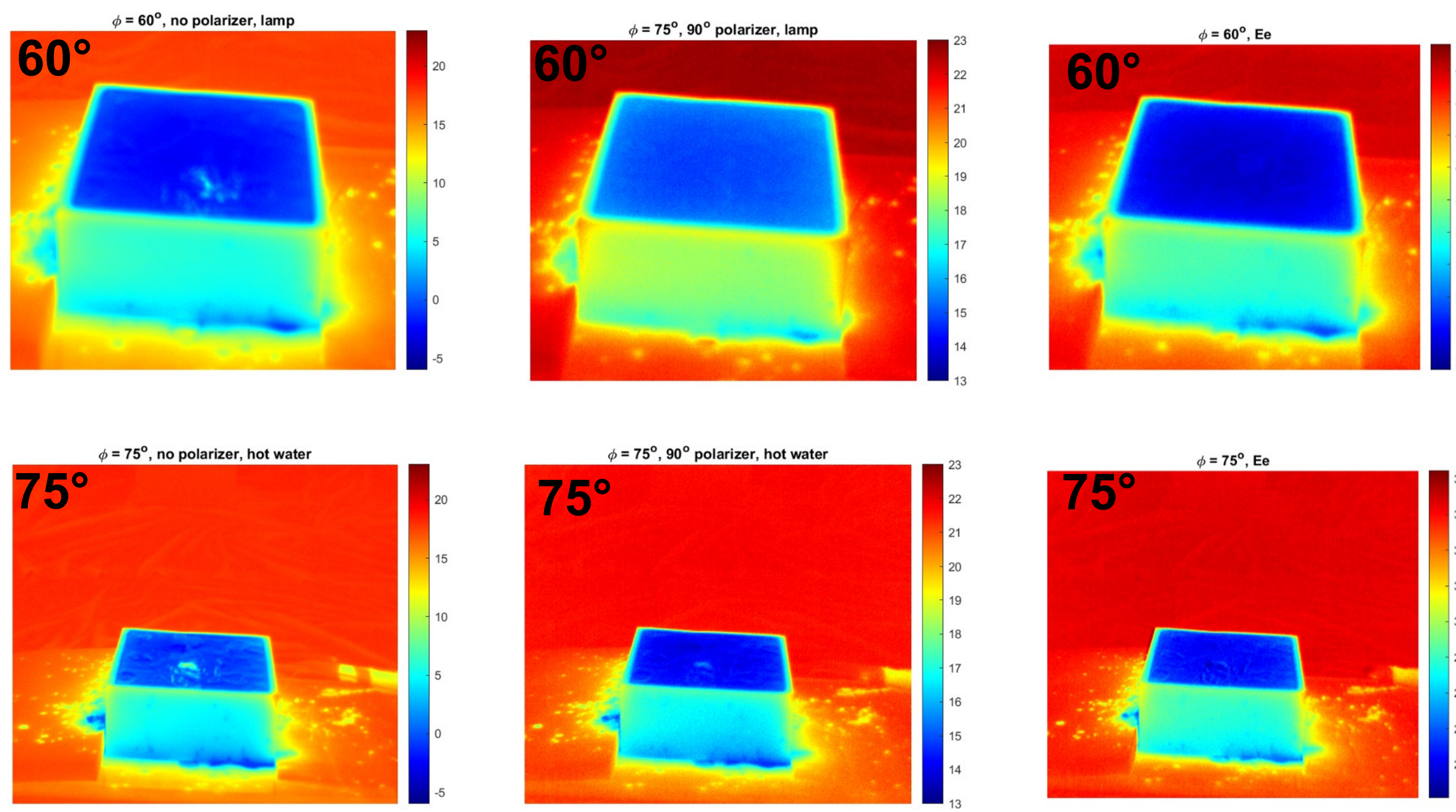


Data Analysis – ice-covered concrete





Original | **Strategy 1** | **Strategy 2**



3. Conclusions & Ongoing work

1.Theoretically predict the reflectivity of concrete with dry, wet, and ice-covered condition.

2. Designed and fabricated the lens-polarizer assembly;

3. Performed laboratory tests to measure the temperature field of dry, wet, ice-covered concrete surface;

4. For dry concrete surface, IR reflections from ambient environment are negligible;

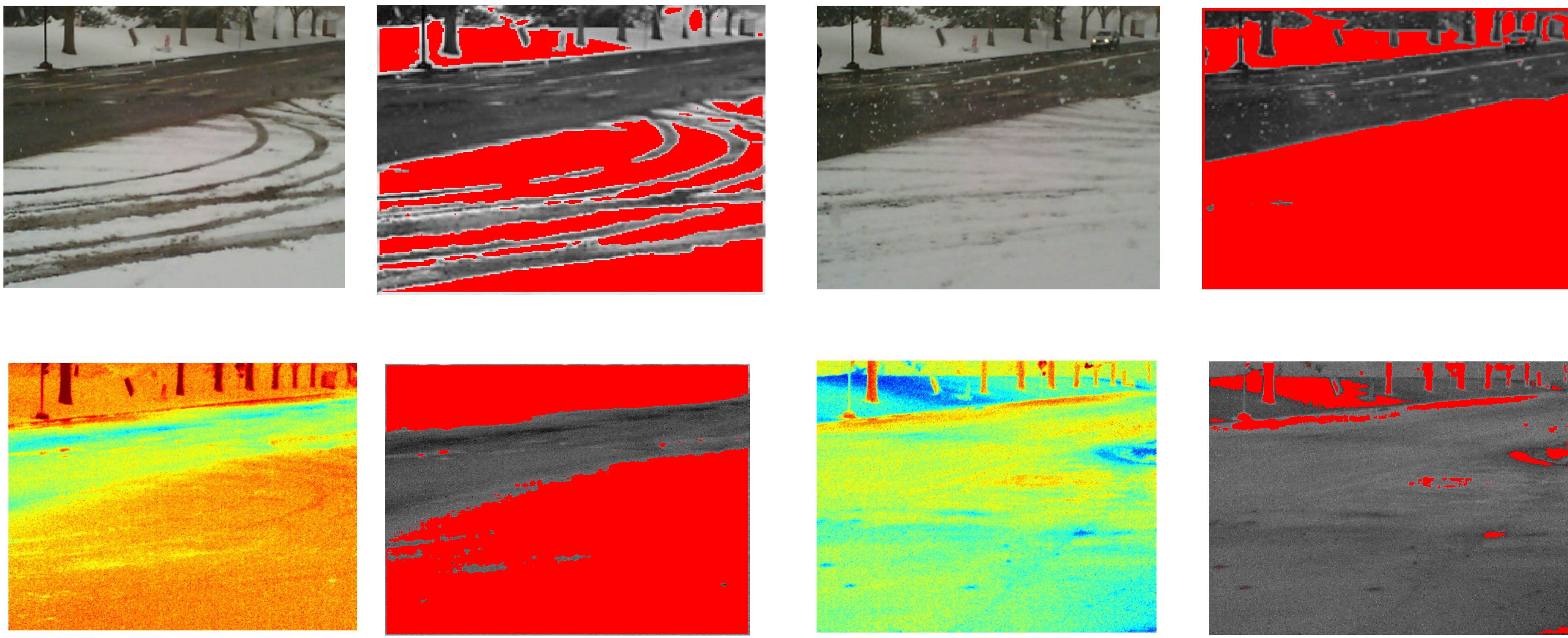
5. For wet and ice-covered concrete surface, IR reflections are significant and can be effectively suppressed by the proposed strategies;

6. Strategy 1 is preferred for field tests considering its effectiveness & easiness in implementation.

3. Conclusions & Ongoing work

Field Data Collection and Dual-sensory Algorithm Development

Pattern recognition development with dual-sensory system



Acknowledgements

- FHWA Aurora Program
- Aurora Board
- Jeff Williams and Cody Oppermann, Utah DOT
- Narwhal group
- University of Utah
- Tina Greenfield, Iowa DOT
- Zachary N. Hans and Neal R. Hawkins, Aurora

Reference

[1] USDOT FHWA Road Weather Management Program website https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm
[2] Strong, C. K., Ye, Z., Shi, X. (2010). Safety effects of winter weather: the state of knowledge and remaining challenges. *Transport reviews*, 30(6), 677-699.
[3] Aurora Project (2005). New Road Surface Condition Sensors. *Aurora Project 2005-06*.
[4] Bridge, P. (2008). Non-invasive road weather sensors. *4th National Conference on Surface Transportation Weather*, Indianapolis, Indiana.
[5] Ye, Z., Shi, X., Strong, C.K., Larson, R.E. (2011). Vehicle-based sensor technologies for winter highway operations. *IET Intelligent Transport Systems*.
[6] Josson, P., Riehm, M. (2012). Infrared Thermometry in winter road maintenance. *Journal of Atmospheric and Oceanic Technology*, Vol. 29.
[7] Reed, J., Barbour, B. (1997). Remote passive road ice sensor system (RPRISS). *IDEA Intelligent transportation systems Project final report*, TRB IDEA ITS-34
[8] Misener, J. A. (1998). Investigation of an optical method to determine the presence of ice on road surfaces. *California PATH working paper*, UCB-ITS-PWP-98-17.
[9] Joshi, P. (2002). A Mobile Road Condition Sensor as Winter Maintenance Aid. *Final Report for ITS-IDEA Project 85*.
[10] Vinnova, AerotechTelub, Hogskolan, Vagverket (2002). Final Report on Signal and Image Processing for Road Condition Classification. *Aurora report 2002-02-06*.
[11] Saito, M., Yamagata, S. (2014). Effect of video camera-based remote roadway condition monitoring on snow removal-related maintenance operations. *Aurora Project 2012-03*.
[12] Schmokel, P. (2004). Development of a wide area optical surface contamination detection system for public transportation application. *Final report for highway IDEA project 83*.
[13] Kubichek, R. F., Yoakum-Stover, S. (1998). Cost-Effective Microwave Sensing of Highway Road Conditions. *IDEA project Final report*, contract NCHRP-31.
[14] Robinson, R., Cook, S. J. (2012). Slippery road detection and evaluation. *Michigan DOT report*.
[15] Castillo Aguilar, J., Cabrera Carrillo, J. A., Guerra Fernandez, A. J., Acosta, E. C. (2015). Robust Road Condition Detection System Using In-Vehicle Standard Sensors. *Sensors, 15*(12).
[16] Albrecht, C. (2005). Pavement temperature sensors. *Aurora project 2001-04*.
[17] SRF Consulting Group, Inc. (2005). Laboratory and field studies of pavement temperature sensors. *Aurora final report*, SRF No.0024544.
[18] Suzuki, S., Ogasawara, N. (2018). Quantitative evaluation of polarized emissivity and polarized reflectivity using infrared thermographic instrument. *Advanced Experimental Mechanics*, Vol. 3.
[19] Williams, J., Oppermann, C., (2018). UDOT Snow and Ice Performance Measure. *Western States Rural Transportation Technology Implementers Forum*, Yreka, CA, June 20, 2018.

Thanks & Questions?