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Executive Summary

Significant hazards caused by snow-covered and icy roads result in fatalities and disruption of the transport of commerce. There is a need for real-time observations and weather forecasts to support timely and efficient decisions to reduce such disasters. Drivers need reliable forecasts and alerts for icy roads, in particular the presence of black ice, to reduce winter driving risk. State traffic and safety management need icy road forecasts to inform winter operations, public notice, snow removal resources, and school re-scheduling. For example, in the state of Montana, where snowfall and cold weather occur more than 70% of the time in winter months, car crashes induced by icy roads have been one key reason for Montana winter road accidents. Nevertheless, the ice formation mechanism, in particular black ice, is not well studied and thus not forecasted by the National Weather Service.

The Icy Road Forecast and Alert system (IcyRoad), an innovative technology developed by SpringGem Weather Information, LLC is based on numerical weather forecasts, remote sensing observations, cloud computing, and data mining to provide ice information to users for any road across the US, 24 hours a day, 7 days a week, with 24-hour lead time. The University of Montana (UM) is working with SpringGem Weather Information through this project to validate and refine the IcyRoad scientific algorithm, in particular black ice algorithm, using Montana Department of Transportation (MDT) Road Weather Information System (RWIS) data and UM's drone-based ice detection technology.

Introduction

Black ice mechanisms are one of the most meteorologically challenging processes to model and more observations are needed to understand black ice forming meteorological conditions, locations, and timing of events in order to forecast it well. Since the road ice observations, RWIS sites, are located only in limited areas along roads, more observations between RWIS sites are needed. Studies have been done using additional sensors such as near infrared cameras (0.9 - 2.3µm) with evidence of possible black ice detection although wet and black ice surfaces had similar sensor responses and new technologies were recommended to improve detection accuracy (Jonsson et al., 2015). New technologies are definitely needed in this project to validate IcyRoad forecasts since visible cameras and RWIS data cannot discern the difference between wet and black ice surfaces. We therefore are developing a drone-based remote sensing technology to detect black ice via hyperspectral camera launched on an unmanned aerial vehicle (UAV). This detection approach could help us to improve physical modeling of black ice which has been ignored in the existing Weather Research and Forecasting model (WRF/land-surface) and could validate the black ice forecast component in the Icy Road Forecast and Alert system. There is evidence of hyperspectral cameras with visible and near infrared capabilities (0.4 – 1 µm) being used to identify road defects (Abdellatif et al., 2019) but no one has yet attempted to distinguish road surface conditions using hyperspectral cameras. This project is using a hyperspectral camera capable of distinguishing 281 spectral bands at 2.1 nm resolution. As a result, an increase of accuracy for IcyRoad forecasts is expected. The forecast algorithm has been developed by SpringGem Weather Information and this project is to conduct data validation and field experiments to validate and refine the technologies.

Black ice is hard to detect from the visible bands (i.e., 0.4-0.7 µm, the wavelength of solar radiation spectrum that human eyes use for sight). Nevertheless, an ice sheet, thin or thick, has spectral reflectance (r_λ) significantly different at near infrared bands. By using the combination of visible bands and near-infrared bands (NIR), a thin ice-covered surface may be differentiated from asphalt surfaces (i.e., road surfaces). Specifically,

$$\text{Road Ice Index } \theta = (\text{NIR-RED})/(\text{NIR+RED}) \qquad (1)$$

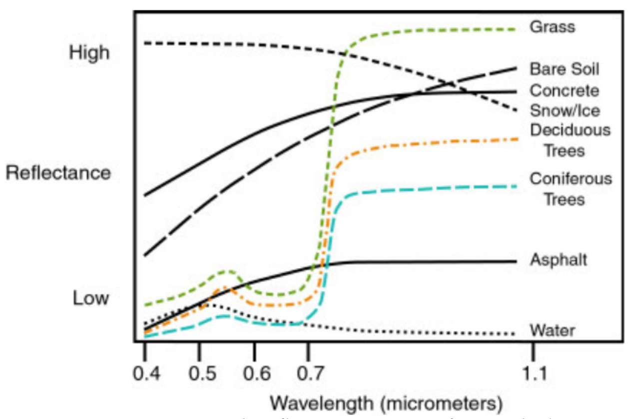

Figure 1:Spectral reflectance curve for asphalt, water, snow and vegetation.

in which RED is the radiance for the red band. The Red band is the edge of the visible band at close to 0.620 – 0.670 µm (e.g., MODIS band 1, King et al. 2004). NIR is the near-infrared region of the electromagnetic spectrum (from 0.78 µm to 2.5 µm) and we will use 0.841 – 0.876 µm (e.g., MODIS band 2) to follow NASA MODIS instrument spectral bands. Theoretically, for snow and ice, r_λ reduces from RED to NIR and thus θ is negative; while for asphalt surfaces, r_λ increases from RED to NIR and thus has a positive θ. As a result, icy roads can theoretically be detected using a combination of Red and NIR bands. Nevertheless, this all depends on the accuracy of the hyperspectral calibration and we are exploring the need to use an additional camera capable of longer bands in the NIR, such as MODIS band 6 (1.628-1.652 µm) since research showed evident spectral difference for dry, wet, snow and icy roads at this band (Hall et al. 2002, Jonsson et. al 2015).

Data Collection

Two main objectives for data collection are;

a) First, we have collected baseline observations of spectral signatures on dry, wet, ice, and possibly black ice on asphalt in a controlled environment. We used the Montana State University Sub-zero laboratory to control temperature and wind conditions while setting up various scenarios on asphalt samples (i.e. snow-ice, old-snow-re-freeze, and possibly black ice cases).

b) We are preparing to use the same hyperspectral camera from the subzero laboratory on an unmanned aerial vehicle to detect road ice conditions at varying altitudes when no traffic is present. In preparing for the drone flights, we are taking more fixed imagery at the Missoula airport since it is a secure site with access to asphalt where we can conduct imaging under a variety of conditions (dry, wet, and ice). We identified runway 26/8 near taxiway C during times when the runway is shut down in the winter.

Current Data Repository

September 21st - 25th, 2020 we collected over 70 GB of data in the Montana State University sub-zero laboratory using two different hyperspectral cameras, UM's Pika L and we borrowed Resonon's Pika L 320 whose range is farther into the NIR than the UM Pika L. This data resides in UM's box cloud storage. Each spatial point (pixel) in the hyperspectral images represents a continuous curve of incoming light intensity versus wavelength. The data can also be interpreted as a stack of images, with each layer in the stack representing the scene at a different wavelength, this "stack" of two-dimensional images is referred to as a "datacube" of three dimensions.

We setup a camera each day and took imagery at air temperatures from 24 degrees F to 40 degrees F at 2-degree increments. We then repeated the measurements from 40 degrees to 24 degrees at 2-degree increments. See figure 2 for experimental setup.

Figure 2: Experimental setup at MSU. The camera and asphalt samples were in the temperature controlled room while data collection happened outside the room. Sample and room temperatures were recorded with each image.

Once an image was recorded we used Resonon's software to calibrate the data based on the calibration panel. We saved both the "raw" and "calibrated" data cubes. We then used

ArcGIS due to Resonon's data format and it is software commonly used by Montana Department of Transportation. We decided to start by calculating the Road Surface Index value using reflectance in the NIR = 1025nm and Red = 389nm where $\theta_{asphalt} = 1$ with no ice or water present and $\theta_{ice} = -1$ with no asphalt showing. According to literature, these wavelengths should give best high and low reflectance of asphalt and ice. Scripts have been written in Python for preliminary image analysis using the ice index formula. Each asphalt sample was divided into quadrants and half of those quadrants were treated with ice or snow. See figure 3, quadrants 1,3,5,7 contained snow/ice/wet except for September 22nd when all quadrants were dry at all temperatures.

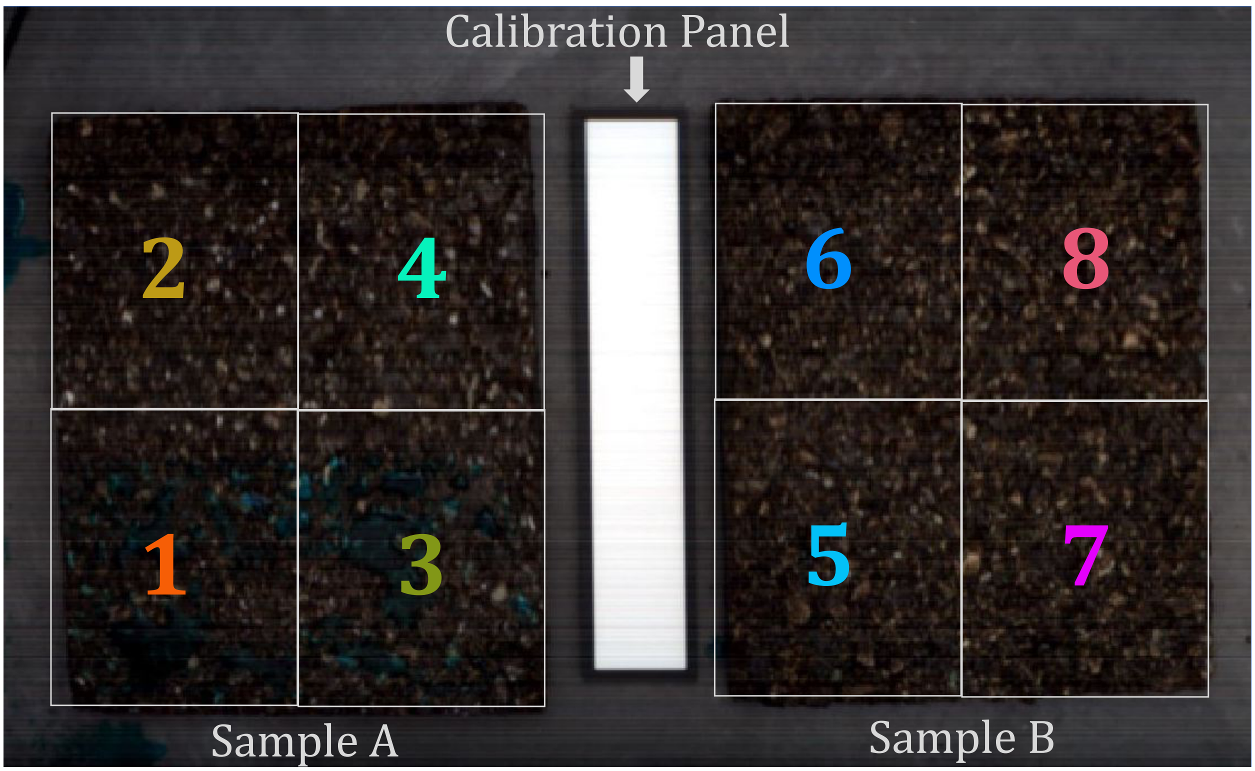

Figure 3: True color image from the Pika L camera of asphalt samples divided into quadrants for analysis. Water can be seen in quadrants 1 and 3 giving off a blueish hue. Colors of the numbers coincide with the graphs under the results section.

Methods

A Python script was written for this task, "Ice_Index_Sample_Mean.py". This code is available in GitHub; https://github.com/jfowler9/MDT_Icy_Roads.git The script inputs TIFF images generated from ArcGIS, makes an array of the pixel values, deletes the pixel values associated with the calibration panel, then averages ice index values by quadrant of each sample. The averages represent both time series and hence room temperature values.

Results

Preliminary results indicate some promise for detecting ice versus dry asphalt using UM's Pika L but discerning black ice from other ice is yet to be determined. As seen in the plots below;

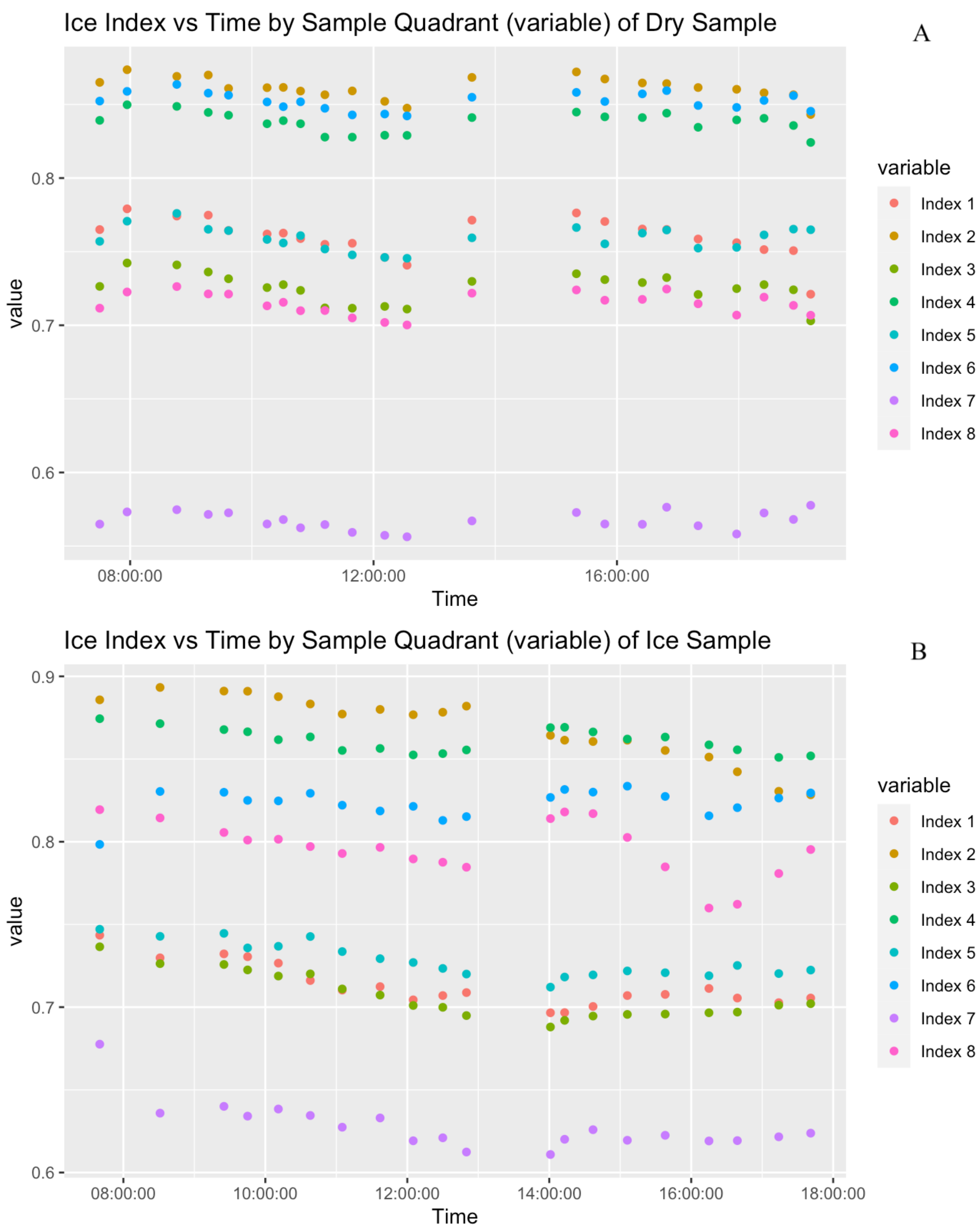

Figure 4: A; plot of ice index value vs time on dry asphalt in all quadrants (variable) for September 22. B; plot of ice index value vs time with wet or iced quadrants in 1, 3, 5, and 7 for September 23. Temperature starts at 22-24F each day rising to 40F before descending again from 1400 – 1800.

Note immediately that there are no negative ice index values so the basic equation does not hold. However, quadrants 2,4, and 6 maintain fairly consistent ice index values from day to day staying between .8 and .9. Quadrant 8 is more variable even though it was dry each day. Some of this variation calls into question the calibration technique as the only differences between days beyond treatment for wet/ice was possible lighting setup. But, the lighting did not change throughout a single day hence the oscillation between 14:00 – 18:00 for quadrant 8 is peculiar. Ice index values in quadrants 1,3, and 5 decrease from dry to ice/wet as theorized. But, the values actually decrease as the water goes through its phase change from ice to liquid remembering temperatures are rising from freezing at 7:30 to 40F by 1230. Then the liquid refreezes between 1400 – 1800. There is also the issue with quadrant 7 with its values increasing between dry and ice/wet treatment. Since quadrant 7 and 8 are aligned vertically as seen in figure 3 this could be a calibration issue in the software and/or experimental setup.

The Pika L 320 (figure 5) showed great promise for discerning the difference between water and dry asphalt using supervised classification via ArcGIS but the camera requires too much lighting to be of use in operations.

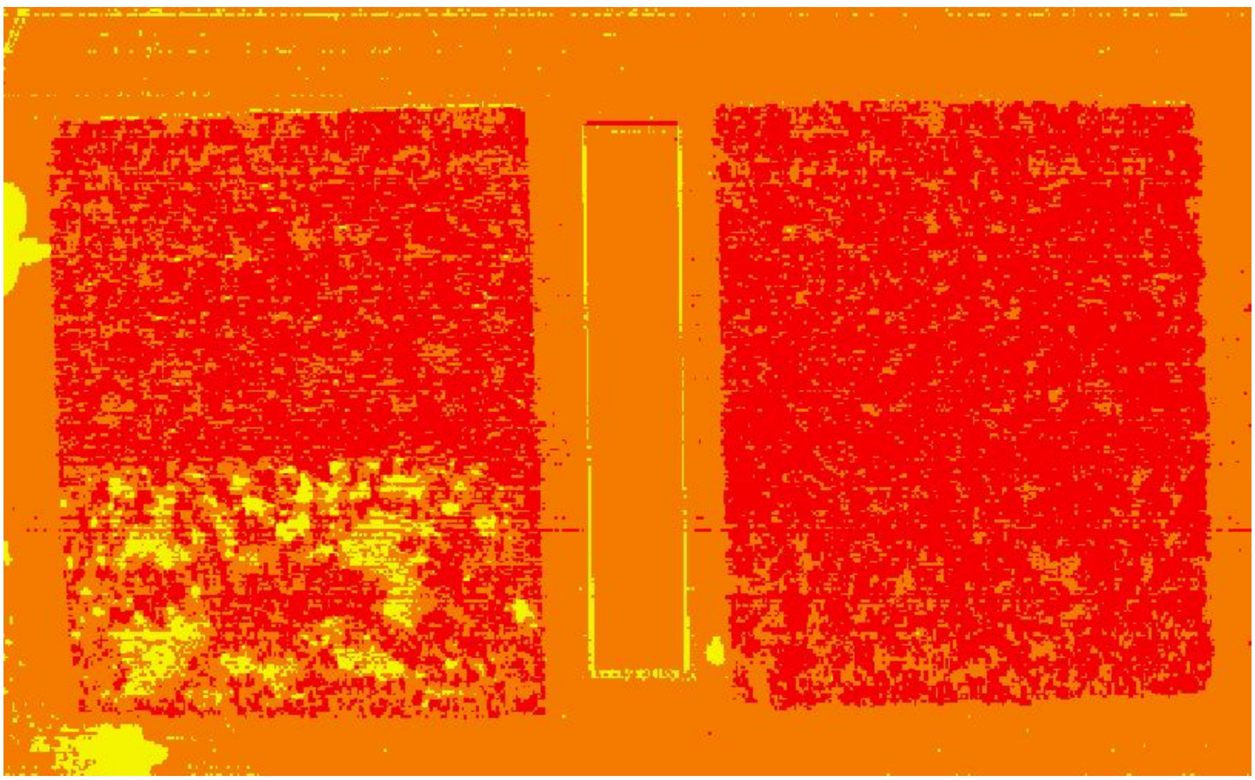

Figure 5: Supervised classified image from ArcGIS of the Pika L 320 camera depicting water in quadrants 1 and 3.

Future Directions

Based on feedback from Dr. Chandler, I will next apply a linear discriminate analysis on the data. Then there is a goal to remove ArcGIS from the workflow and choose NIR and Red wavelengths to optimize results. A python script has been started to pull in the calibrated data cube for each image directly then I will apply a principal component analysis (PCA) to reduce the dimensionality of the data. PCA is a popular and widely used dimensionality reduction technique for hyperspectral data.