Developing Smart Tools for Black Ice Detection and Real-Time Warning Systems Considering Traffic Safety of Road Network Infrastructure

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1 INTRODUCTION

Black ice is a thin coating of glazed ice on a surface such as a road. Black ice is not black but visually transparent, allowing the road to be seen through it. Thus, black ice appears black on a road surface and gray or tan on a concrete road surface. Black ice road looks exactly like a wet road but with less vehicle tire friction. Black ice can be formed in many ways but the most common one is from melting snow on or beside the road during the winter season. After a winter storm, snow melts into the water when the day temperatures climb above freezing temperatures. With another sharp dip in temperatures (i.e., below 0^{o} C) in the afternoon or during the night, any standing water turns into black ice with a combination of pollutants such as dust. Black ice can also occur from rain or fog events when the moisture remains on a surface and is subsequently exposed to freezing or sub-freezing temperatures. Figure 1 shows a typical representation of black ice on pavements.

Figure 1: An Example of Black Ice on the Roadways.
(Source: WCNC Charlotte, 2022)

Black ice poses a serious threat to vehicular traffic and is considered a potential factor in many traffic accidents, especially in North America. According to the Federal Highway Administration (FHWA), nearly 200,000 auto crashes occur annually due to icy pavement, accounting for over 10% of all weather-related crashes in the U.S. Moreover, icy surface causes an average of 700 fatalities and over 65,000 injures annually (FHWA, 2020). These circumstances clearly indicate the necessity of some technological advancement that can detect black ice beforehand and thus prevent crashes. On the other hand, in the era of commercialization of Semi-Autonomous Vehicles (A.V.s), real-time warnings of locations of black ice on roads are crucial to prevent fatal accidents involving A.V.s.

1.1 Problem Statement

Very limited research has been found in the literature on preventing black ice-related crashes, even though they are the main reason for large-scale crashes in winter. In the State of Wyoming, a high number of roadway users and drivers encounter slick sections of pavement due to the short-term fluctuating temperatures during winter seasons. Such fluctuations in temperature cause the snow accumulation on roads to freeze, melt, and then re-freeze on pavement surfaces. These frequent events reduce the friction between pavements and tires significantly. In addition, highway drivers in Wyoming face additional challenges of low visibility during storms from blowing snow, making the visual detection of slick roads more difficult. As a result, more than 19,000 crashes were reported by WYDOT in the past ten years due to snowing and slipperiness conditions.

WYDOT reports slick road conditions across some locations on road networks. However, some sections, surfaced with invisible black ice, are hard to detect unless slipperiness events are occurred and reported. There is an urgent need to develop an integrated system to detect the black ice formation and provide early warnings for road users and authorities. The data and warning systems being shared will help WYDOT consider precautions and prompt decisions of treatment and/or closures to reduce slipperiness-related crashes. Therefore, this study aims to develop smart systems that can be mounted on both vehicles and roadside infrastructure for a reliable way to detect black ice and distinguish between safe and potentially dangerous driving situations. The need for roadside detection is crucial since detection by a vehicle only provides a few seconds of warning to a driver to prevent an accident. The study proposes developing a smart sensor fusion system equipped with near-infrared (NIR) source thermal camera, visible spectrum camera, and humidity/temperature sensor modules with machine learning algorithms to identify dry, water, black ice, ice, and snow. In support of this broader goal, the study is aimed to fulfill the following main phases.

1.2 Research Outline

The first part of this research will focus on the traffic safety analysis for black ice and slipperiness-related crashes in Wyoming. The analysis will show the main contributing factors affecting such crash rates and frequencies. In addition, a spatial analysis will be conducted, showing the heatmaps of black-ice-related crashes on the different roadway categories, including interstates, national highway systems (NHS), and non-NHS. The results from this part will provide a preliminary understanding of the consequences of black ice development on the safety of vehicular traffic in Wyoming.

The second part of this research will address the following tasks:

1. A black ice prediction model using meteorological and Geographic Information Systems (GIS) data from the WYDOT Road Weather Information System (RWIS: https://www.wyoroad.info/pls/Browse/WRR.RWIS) and WYDOT Geographic Information Systems (GIS: https://gis.wyoroad.info/). A Machine Learning model will be developed to compute the Black Ice risk index (BRI) ranging from 0 to 1 reflecting the probability of black ice formation.
2. A prototype device to detect black ice in real-time will be developed that can be mounted on the front end of a WYDOT snowplow with communication capability (WiFi or Satellite) to interface with real-time warning systems.
3. Establish an experimental laboratory set up to create black ice and measure specular reflected light power to create a dataset for training a machine learning algorithm. The dataset would be made available to WYDOT, which has significant value since data is the most important component to develop any machine learning algorithms.

The research will also provide a detailed review of the intelligent transportation systems (ITS) applications for capture and management techniques of real-time black ice data. Such applications will benefit both roadway drivers and road authorities for immediate reactions to avoid the risk of skidding crash events. The data will be utilized in real-time warning systems so that smart and integrated systems are expected to be implemented in Wyoming.

2 OBJECTIVES

The study aims to fulfill the following objectives:

- Reduce crash severities and frequencies for black-ice-related crashes in Wyoming.
- Develop a smart decision-making system for managing vehicular traffic on slick roads.
- Utilize WYDOT RWIS and GIS database to predict the probability of black ice formation.
- Utilize state-of-the-art black ice detectors using infrared and artificial intelligence technologies.
- Find best practices for black ice data capture and sharing in Wyoming using ITS applications.

3 EXPECTED BENEFITS

The primary benefits of this study include:

- Promote the intelligent integration between vehicles and infrastructure systems using real-time condition data.
- Reduce frequency and severity of black ice-related crashes in Wyoming.
- Enhance driving conditions of vehicles on Wyoming's roads during winter seasons.
- Make prompt effective decisions of warning, closure, and treatments to reduce the number of crashes on slick roads.

4 BACKGROUND

Unfortunately, the existing static roadside warning signs (such as "Bridge May Be Icy"), as shown in Figure 2, simply could not pull out enough attention to drivers, and hence they often underestimate the situation. Before the reporting of a dangerous level of black ice presence made by the authorities, a number of ice-caused crashes could have already occurred. Flashing signals with a reduced speed limit or slick spots alert on variable message signs (VMS), as shown in Figure 2, are much more effective than static signs to draw drivers' attention and reduce traffic accidents. With the installation of such warning signs, the black-ice-related crashes were expected to reduce. However, the continuous rise of fatalities and injuries on roads from the black ice have made the researchers concerned to develop a more advanced system to detect icy spots.

Figure 2: An Example of Warning Signs for the Possible Presence of Black Ice on the Roadways.
(Source: Roadside Linguistics, 2012; Live Storms Media, 2021)

Globally, the following three studies were found in the literature implementing smart systems for black ice detection and warning systems proposed at the large-scale.

4.1 Oklahoma Department of Transportation Decision Support System

Liu et al. (2014, 2017) in collaboration with the Oklahoma Department of Transportation (ODOT) initiated a research project that developed a prototype decision support system (DSS) to predict and detect black ice formation and pinpoint dangerous road sections. The system relies on a regular temperature and conductivity sensors to detect the formation of ice on pavement services. After comparing several ice detection techniques, an electrical conductivity (E.C.) sensor is selected. A lab test was conducted to test the effectiveness of the developed tools using a platform of freezer, humidifier, three thermocouple sensors, two E.C. sensors, three fans, Campbell Scientific datalogger, control box, concrete sample, and asphalt sample. The results show potential effectiveness of the detection tool. However, false detection alarms were noticed during specific controlled conditions, including extra humidity, temperature decrease, and sudden wind blows.

The study recommends conducting field tests before implementing the system, and the threshold values should be calibrated based on the field test results. So, the study is still under development phase and needs some field tests before full blown implementation. In addition, the efforts of this research were expanded to include recommended decision-making systems. Such systems include a correlation with weather conditions to predict the black ice risk index. Another tool of data visualization was proposed to store, analyze, and introduce the black ice data to both road users and authorities for prompt actions of closures and warning systems. Figure 3 demonstrates the architecture of the proposed Black Ice Detection and Warning Decision Support System (BIDWDSS).

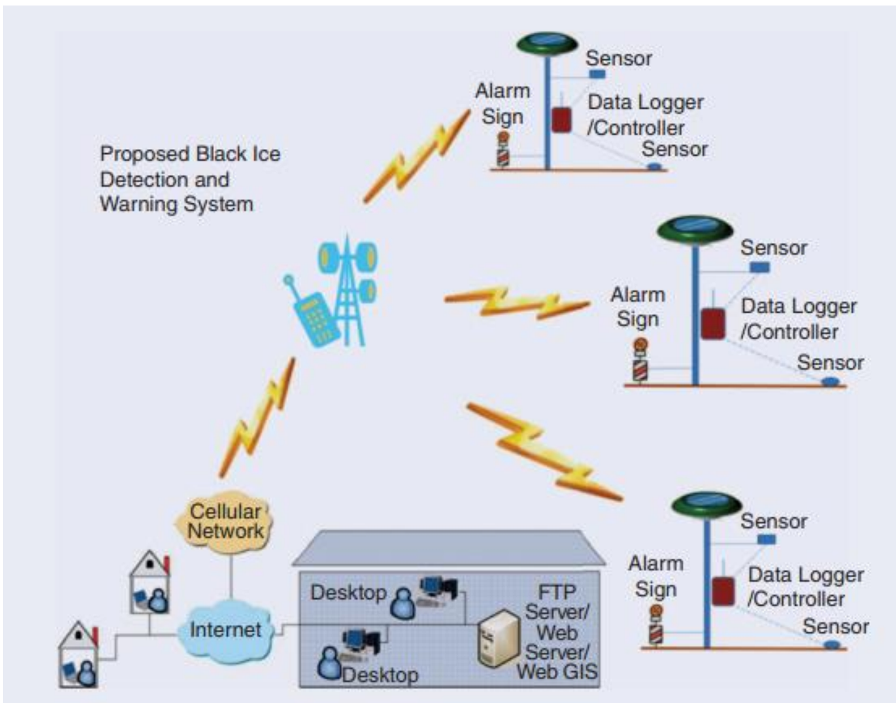

Figure 3: Architecture of the Proposed BIDWDSS.
(Source: Liu et al., 2017)

4.2 Real-Time Black Ice Detection in Finland

In Finland, a real-time data management system was developed by EEE Innovations Ltd and VTT Technical Research Center of Finland. The system includes a patented software to track a vehicle encountering a slippery road surface. Then, the system can automatically transmit the spatial data to other drivers set up with the same software. The spatial data analysis provides early warning to drivers approaching the previously defined slick sections. The slick locations are also shared with road maintenance vehicles to respond immediately with restorative actions.

Figure 4 shows the general architectural of the black ice detection and data management system proposed. In fact, the patented software doesn't require installing any additional equipment since it can be operated by the in-vehicle operating system and vehicles' computer.

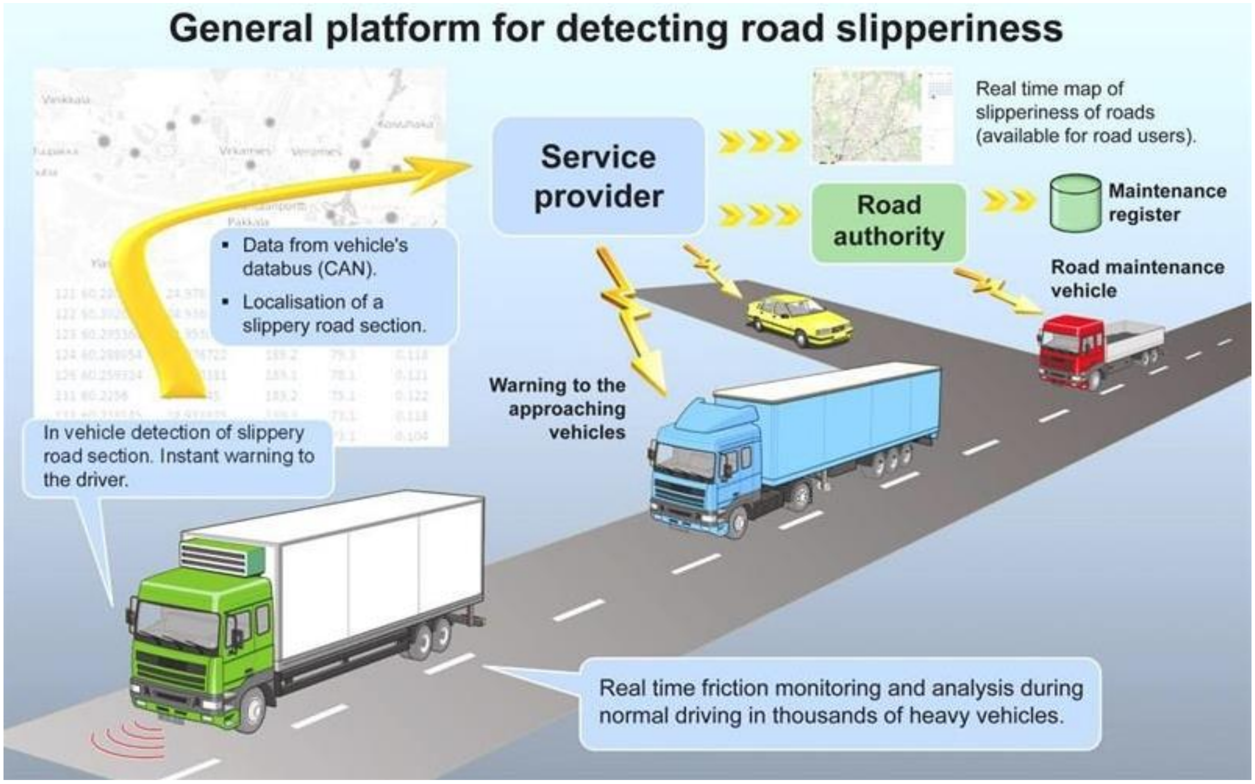

Figure 4: Architecture of the Real-Time Black Ice Detection System Proposed in Finland.
(Source: VTT Technical Research Centre of Finland, 2017)

During the winter season of 2015-2016, four field tests was conducted for heavy trucks having software systems equipped with the developed technology. The results show that the system can detect the slippery road conditions accurately and in real time. In 2018, a pilot study was sponsored by EEE Innovations, Finnish Transport Agency, and Trafi to expand the data collected by the developed software using 1000 heavy traffic vehicles in Helsinki (Lebreton, 2018). The EEE Innovations Company believes that the system will enhance the safety and welfare of the road users and enhance the real-time warning systems for black ice detection on roads. However, no further information was found for the actual implementation of this project in the literature. The efforts are limited within the pilot study developed in 2018.

One major limitation of the developed systems is that it lacks actual sensors of black ice detection tools. Although the companies mentioned that the software can detect slippery roads, the system actually tracks the vehicle performance traveling on slick pavements, based on the data collected by the car's own sensors (Domela, 2013). With such practices, the system is expected to include only events with activated slipperiness warning systems in the vehicles. In case the driver was able to take extra precautions on the road in adverse weather conditions, such as reducing speed and avoiding sharp maneuvers, the slipperiness event could be avoided and the system will not be able to track the black ice locations. Hence, using both mounted black ice detectors/sensors and in-vehicle tracking system can provide more extensive data of black ice locations.

4.3 Artificial-Intelligence-Based Detection Plan in Korea

Another recent study was conducted by Lee et al. (2020) in Korea. The study presented a Convolutional Neural Network (CNN)-based black ice detection plan to prevent traffic accidents of Automated Vehicles (A.V.s) caused by black ice. A total of 2230 image data were collected using Google Image Search. To conduct learning, image data was transformed into black and white format. Test results indicated that the proposed CNN model detected black ice with 96% accuracy and reproducibility. Thus, the study provides an insight into improving the safety of A.V.s and preventing black ice accidents in advance. It is expected that the camera attached to the vehicle will be able to detect black ice in advance. In addition, CCTV is expected to become an important medium for C-ITS (Cooperative Intelligent Transportation System) in the future. However, the study was limited to only the algorithms developed for machine learning and image processing. No further efforts have been conducted for the actual implementation. Also, the grayscale transformation of the images provided some limitations in the detection performance of the smart tool.

4.4 Other studies

Chen (1991) examined using image analysis to detect black ice. Holzwarth and Eichhorn (1993) developed non-contact sensors to examine road texture, wetness, and ice on road surfaces, and a prediction model was established. Gailius and Jačenas (2007) investigated road ice detection by analyzing tire-to-road friction ultrasonic noise. Trevino et al. (2007) analyzed black ice detection on an open-graded friction course, using moisture and temperature sensors embedded in the pavement. In addition, there are a few U.S. patents on detecting road surface conditions (Stolarczyk and Stolarczyk, 1997; Chang and Fanning, 1998; Survo and Haavasoja, 1998).

However, the limitation lies with these detecting methods where it is difficult to reliably estimate ice formation from any of these sensors due to the prevalence of extraneous noise factors.

Based on the previous studies, the methods used for detecting black ice include sensors (Tabatabai et al., 2017; Alimasi et al., 2012; Abdalla et al., 2017), sound waves (Minullin et el., 2011; Gailius and Jačenas, 2007), and light sources (Ma et al., 2020). Tabatabai et al. (2017) explored to detect black ice, ice, and water in roads and bridges using sensors embedded in concrete. In this study, a sensor was proposed through the change of electrical resistance between stainless steel columns inside concrete to detect the road surface condition. By conducting experiments under various surface conditions, it was concluded that the proposed sensor can effectively detect the road condition. Alimasi et al. (2012) developed a black ice detector consisting of an optical sensor and an infrared thermometer. The study was conducted on a total of six road conditions (dry, wet, "sherbet", compact snow, glossy compacted snow, black ice) and diffuse reflection and reflection. As a result of the experiment, black ice was found to have a large specular reflection (R.S.) with a small diffuse reflection (R.D.), resulting in a low (RS/RD) value. Abdalla et al. (2017) introduced a system for detecting black ice using Kinect. The types of ice were classified into soft ice, wet snow, hard ice, black ice where the thickness and volume of the ice were measured using Kinect. Experiments have demonstrated that the types of ice formed in the range of 0.82 m to 1.52 m from the camera can be distinguished, and the error rate of measured thickness and volume is very low, indicating that black ice can be detected by utilizing Kinect. Ma et al. (2020) analyzed a black ice detection method using a three-wavelength non-contact optical technology. The study applied three wavelengths (i.e., 1310 nm, 1430 nm, 1550 nm) to distinguish dry, wet, black ice, ice, and snowy conditions. The results confirmed that black ice was detected through the reflectance of each wavelength, and it was concluded that it can be used as basic data for the development of equipment to detect road conditions.

4.5 Remarks

Despite the previous efforts of using detection tools for black ice, very limited integrated systems have been adopted for enhancing the traffic safety of roads. The different techniques have not been evaluated at the large scale to test the possibility of utilizing the system at the network level. In addition, some of the developed sensors are not practical due to their complexity and/or high costs (Liu et al., 2014). The lack of having actual implementation of the developed methods on road networks with different weather conditions and high black-ice-related crash rates do not provide a comprehensive evaluation of such smart systems on the safety of roads. This study develops a comprehensive analysis of traffic safety and field evaluation using a novel prototype of black ice detection. The study will propose the strategies for full implementation of the developed decision support system for WYDOT considering feedback from field testing and large-scale analysis. Based on the results of this study, WYDOT will be able to utilize the system to reduce crashes due to black ice.

5 METHODLOGY

This section briefly describes some of the main techniques that will be used in the study.

5.1 Developing Safety Performance Functions

Safety performance functions are negative binomial (N.B.) models. Since Poisson models assume that the mean of the crash frequencies is equivalent to the variance of the crash frequencies and hence overdispersion is not permitted, N.B. models will be developed in this study. Overdispersion is the condition where the variance of the crash frequencies is greater than the mean of the crash frequencies. Under the N.B. model, the risk P_i, of experiencing y_i crashes on a specific segment, i, is computed as follows (Roy et al. 2022):

$$P_i(y_i) = \frac{\Gamma\left(y_i + \frac{1}{k_i}\right)}{y_i! * \Gamma\left(\frac{1}{k_i}\right)} \times \left(\frac{\frac{1}{k_i}}{\frac{1}{k_i} + \lambda_i}\right)^{\frac{1}{k_i}} \times \left(\frac{\lambda_i}{\frac{1}{k_i} + \lambda_i}\right)^{y_i} \tag{1}$$

In the formula, λ_i, k_i and $\Gamma(.)$ are the mean crash frequency, dispersion parameter and gamma function respectively. The NB model's variance function is expressed as (Roy et al. 2022):

$$\mathrm{Var}(y_i) = \lambda_i(1 + \lambda_i k_i) \tag{2}$$

The mean crash frequency is obtained using the following expression (Roy et al. 2022):

$$\lambda_i = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p + \theta_i) \tag{3}$$

The X's are the crash precursors while the β's are their respective coefficients obtained using maximum likelihood estimation.

The mean is the SPF's crash count prediction, $N_{SPF\,i}$. It is formulated as follows (Roy et al. 2022):

$$N_{SPF\ i} = \exp\left[\beta_0 + \beta_1 \times \ln(AADT_i) + \left(\sum_{j=1}^{J} \beta_j X_{ji}\right) + \ln(L_i)\right] \tag{4}$$

5.2 Developing Statistical Model to Identify Hotspots

To identify hotspots of black-ice related crashes, an advanced statistical technique, known as Empirical Bayes (E.B.) will be implemented. To correct for the regression-to-the-mean bias associated with typical hotspot identification method, many researchers advised E.B. technique (Washington and Chen, 2005). E.B. technique follows that safety of a site is affected by some common measurable factors shared by a corresponding reference population as well as by some unique characteristics associated with the site (Chen and Washington, 2008). The expected safety of a site is then expressed as follows (Chen and Washington, 2008):

$$\lambda_i = wE[\lambda] + (1 - w)x_i \tag{5}$$

Here, w is a weighting factor that is calculated through the following equation (Chen and Washington, 2008):

$$\mathrm{w} = \frac{\mathrm{E}[\lambda]}{\{\mathrm{E}[\lambda] + Var\ [\lambda]\}} \tag{6}$$

In Equations 5 and 6, E[λ] represents expected safety of a reference population, Var[λ] is the corresponding variance and x_i is the observed count history for site *i*.

5.3 Modeling the Severity of Black-Ice Related Crashes

In order to identify the factors that affect the severity of black-ice related crashes, advanced statistical method such as Bayesian binary logit models with both fixed and random-effects will be applied. The limitation of classical logistic regression models can be overcome by using Bayesian models which treat the model variables random and the data is used to simulate the behavior of the variables in assessing their distributional properties (Haq et al., 2020). The general form of logistic regression can be expressed as follows:

$$logit\ (\pi) = \log\left(\frac{p}{1-p}\right) = \left(\beta_o + \mu_j\right) + \sum \beta X \tag{7}$$

B_o in Equation 7 is the intercept, x is the vector of explanatory variables, β is the regression coefficients and μ_j is the random effect parameter accounting for the random variation. The posterior distribution of the parameters in a Bayesian modeling framework is given by the following equation (Haq et al. 2020):

$$\text{Posterior} = \frac{\text{Likelihood x Prior}}{\text{Average Likelihood}} \tag{8}$$

$$\mathrm{p}(\theta \mathrm{y}) = \frac{p(y\theta)\mathrm{xp}(\theta)}{\mathrm{p}(\mathrm{y})} \tag{9}$$

θ in Equation 9 is parameter to be estimated, p(yθ) is the likelihood function, p(θ) is the prior information of the parameters, and p(y) is the marginal distribution of y as shown in the following Equation (Haq et al. 2020):

$$p(y) = \int p(y, \theta) d\theta \tag{10}$$

Since p(y) is independent of θ, the posterior is only proportional to the product of likelihood and prior, which is shown in Equation (11):

$$p(\theta y) \propto \mathrm{P}(\mathrm{y}\theta) x\, p(\theta) \tag{11}$$

To assess the random effects, an intra-class correlation coefficient (ICC) will be used and odds ratio will be used to interpret the effects of significant variables. ICC will be calculated using the following equation:

$$ICC = \alpha_c^2/(\alpha_c^2 + \alpha_o^2) \tag{12}$$

In Equation 12, α_c^2 is the between crash-variance of the random intercept model, and α_o^2 is the occupant-level variance.

5.4 Black Ice Detection Sensors and Testing Protocols (EECS)

The first research task involves developing a machine learning model trained using data from the WYDOT RWIS and GIS databases. The WYDOT RWIS consists of data collected from Statewide Weather sensors located on various routes. A machine learning model training dataset consisting of the parameters listed below as input parameters will be developed:

- Surface Status (Dry, Moisture, Wet, Light or Moderate or Heavy Snow, etc)
- Surface Temperature

- Wind Average Speed
- Dew Point
- Humidity
- Air Temperature

The WYDOT GIS database will provide input parameters identifying whether a location is a bridge/underpass, mountainous, etc. Using these input parameters, a Machine learning model using the decision tree architecture will be developed. One of the advantages of a decision tree architecture is that it provides reasons for why the model predicts that there is a low or high probability of black ice formation, which is important for a user to have confidence in the predictions. Furthermore, the real-time data collected by the sensor fusion system mounted on a Snowplow will be used to supplement/complement the WYDOT RWIS data since the RWIS data is not available from all routes.

The second research task involves the development of a smart sensor fusion system consisting of a near-infrared (NIR) sensor consisting of a thermal/hyperspectral camera, visible spectrum camera, and temperature/humidity sensor module with machine algorithms to detect road conditions. The sensor fusion system is proposed to address the environmental effects such as radiation and heat flow which affect the thermal readings, and the low light conditions affect visible spectrum camera function and the inability to differentiate water and ice. The block diagram of the sensor fusion system is shown in Figure 5.

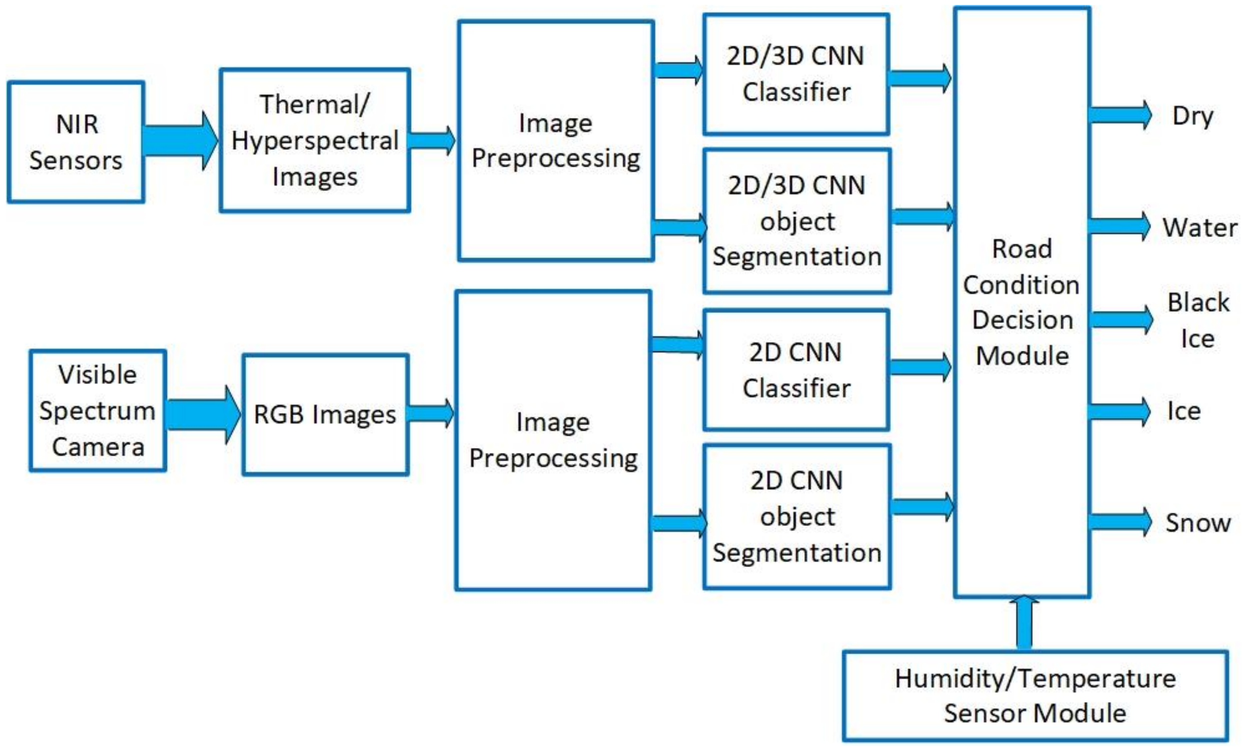

Figure 5: Black Ice Detection Sensor Fusion System

The proposed sensor fusion system to detect black ice consists of two sensor modules interfaced with two machine-learning inference modules. The NIR sensor provides real-time grayscale/hyperspectral images, while the visible-spectrum camera provides real-time RGB images of a road. Examples of raw thermal/hyperspectral data (image) with different bandpass wavelength filters and RGB images of a road with ice, water, snow, and black ice conditions are shown in Figures 6 and 7:

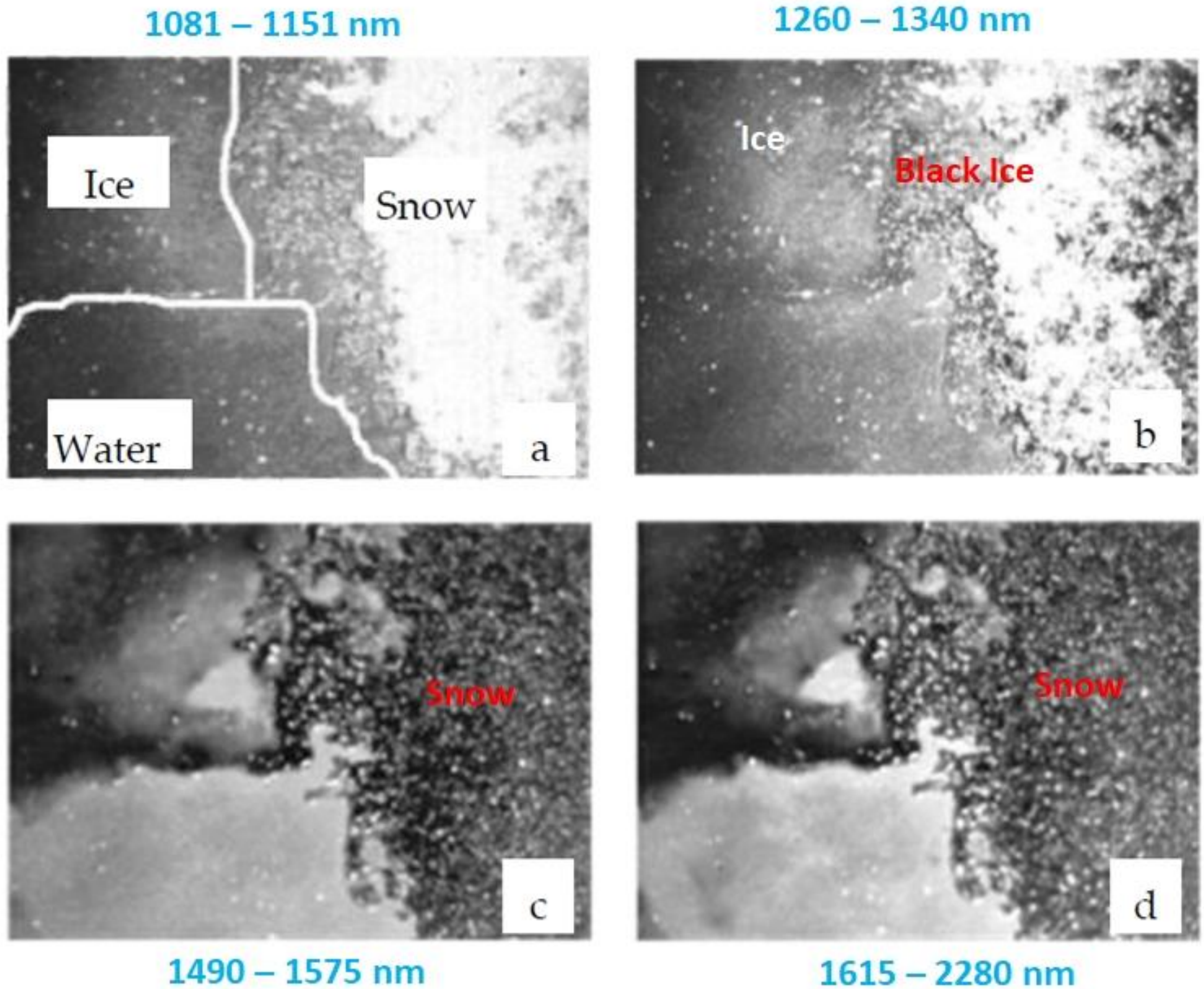

Figure 6: Thermal/Hyperspectral images of a Road from a NIR thermal camera (Source: Internet)

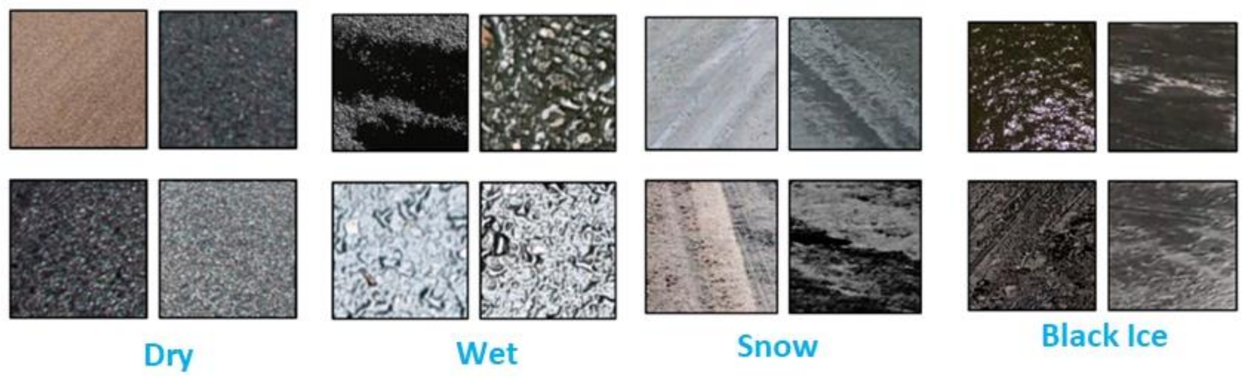

Figure 7: RGB images of a Road from a Visible Spectrum Camera (Source: Google Image database)

The thermal and RGB images shown in Figure 7 are presented as inputs to two machine learning inference deep learning network modules. Each inference module consists of two D convolutional neural networks (CNN). The first CNN in each inference module trained to classify thermal/hyperspectral and RGB images will output the probability of an image representing dry or wet road conditions. In parallel, thermal/hyperspectral and RGB images are also processed by the second CNN of each interface module trained to segment the image into dry, water, black ice, ice, and snow areas (segments) and provide probability outputs for each type of road condition. A total of eleven probability outputs are fed into the road condition decision module, which combines these probability values with the real-time humidity and temperature measurements to produce a warning message containing the road condition information. Since black ice formation is dependent on temperature and humidity levels, real-time temperature and humidity measurements are used to reduce false positive and false negative detections.

6 STUDY TASKS

The study's goals can be achieved by performing the following tasks:

6.1 Literature Review

A comprehensive literature review will be conducted regarding the existing research studies and testing techniques for detection tools. In addition, similar decision support systems will be reviewed for intelligent interaction between infrastructure and vehicles.

6.2 Collect traffic safety data.

A comprehensive crash data will be secured from WYDOT. The data will comprise the crash events with important parameters, including traffic, road geometry, pavement conditions, and environmental data.

6.3 Develop safety performance functions to predict black ice related crashes

To understand what factors contribute to black ice related crashes, safety performance functions (SPF) will be developed. Extensive crash and traffic data, road geometry, pavement condition and environmental characteristics data of Wyoming will be utilized to develop SPFs. SPFs are negative binomial models which permits over dispersion. The developed models will be helpful in identifying factors which affect black ice related crashes in Wyoming. Therefore, the models can be used in a variety of ways to improve safety.

6.4 Investigate hotspots of black ice related crashes

For road network screening, also known as hotspot identification, advanced statistical technique, known as 'Empirical Bayes' (E.B.) will be implemented. The identification of sites which suffer from black ice related crashes is extremely important to implement treatments which will reduce such crashes. A GIS map could also be developed in this regard to identify hotspots of such crashes. Such maps will help WYDOT to identify locations where treatments need to be applied.

6.5 Developing statistical models to minimize the severity of black ice related crashes

To investigate the factors that affect the severity of black ice related crashes, statistical models will be developed. Different driver, vehicular, environmental, roadway related factors will be incorporated in the statistical models to investigate how they affect the severity of such crashes. The factors which will be identified influencing severity of black ice related crashes will be helpful to implement countermeasures which will reduce the severity of such crashes.

6.6 Identify the types of sensors and thermal cameras recommended for the study. (EECS)

The following types of sensors and cameras have been evaluated for use in the laboratory and roadside installation:

- Tri-wavelength Sensor Module

    - RS-7-1 Benchtop Uniform NIR Light Source from Gamma Scientific
    - Halogen lamp
    - Optical Spectrometer from Galaxy Scientific
- Roadside Thermal/Hyperspectral and Visible Spectrum Camera Modules
    - FLIR SC7000 series and Specim HS-CL-30-V10E (400 – 1000 nm) Thermal/Hyperspectral Cameras
    - NVidia Jetson Visible Spectrum Camera
- Humidity/Temperature Sensor Module
    - DHT22 Sensor
- Embedded Computer
    - NVidia Xavier
    - NVidia 5G/LTE Cellular Modem Kit

6.7 Develop a laboratory experiment to detect water, snow, and black ice. (EECS)

The third research task involves setting up an experimental black ice test bed for generating datasets. Machine learning inference modules' performance depends on the availability of a large number of thermal/hyperspectral and visible spectrum images depicting different road conditions under varying environmental conditions such as temperature, humidity, light conditions, etc., for training the deep learning models, specifically the CNN models. Currently, a data set consisting of a large number of thermal images depicting different road conditions under varying environmental conditions is not available. The Google image database consists of only 2,230 RGB images depicting different road conditions. Hence, we propose a laboratory setup to simulate different road conditions and generate thermal and visible spectrum image training datasets. The dataset would be made available to WYDOT, which has significant value since data is the most important component in developing machine learning algorithms.

The laboratory simulator consists of five modules: asphalt, Tri-wavelength Sensors, thermal camera, visible spectrum camera, and humidity/temperature sensor, as shown in Figures 8 and 9.

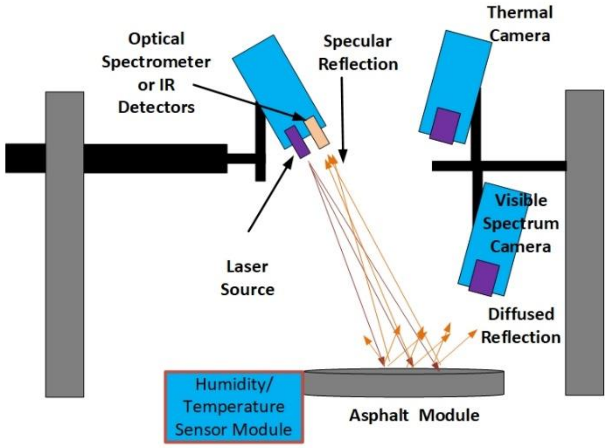

Figure 8: Laboratory Simulator to generate training datasets

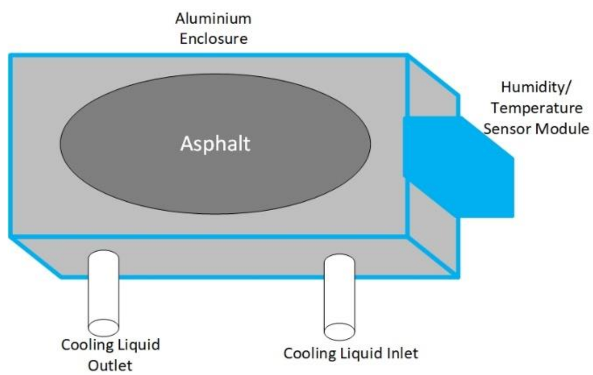

Figure 9: Asphalt Module for Simulating Road Conditions

A brief description of the tri-wavelength and camera modules is provided below:

- Tri-Wavelength Sensor Module

  The tri-wavelength module consists of a NIR laser source such as a tunable NIR source such as the RS-7-1 Benchtop Uniform Light Source from Gamma Scientific or a simple halogen lamp producing 900 – 1700 nm NIR for irradiating the asphalt module, and Optical Spectrometer from Galaxy Scientific or three individual photodetectors to measure the specularly reflected signal levels of 960 to 1950 nm wavelengths. The laser source is used to generate NIR of different wavelengths to irradiate the asphalt module, as shown in Figure 10:

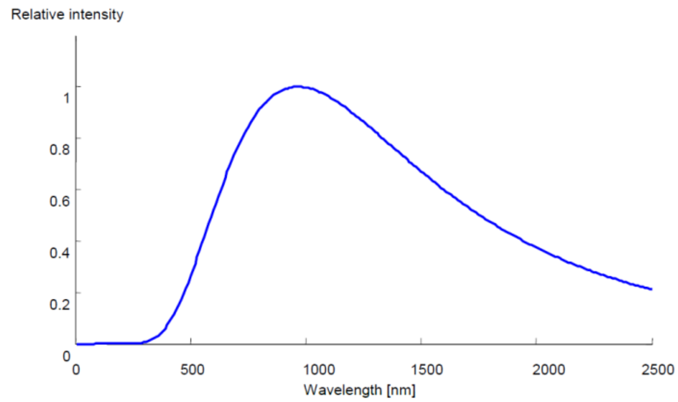

Figure 10: Spectral Intensity of a NIR Laser Source (Source: Shimadzu_Corp., 2015)

The measured specular reflectance using the IR detectors of different wavelengths is shown in Figure 11:

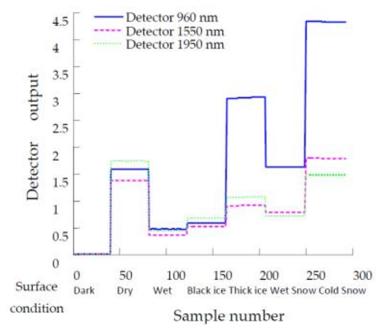

Figure 11: Specular Reflectance Output of road conditions (Source: Jonsson Patrik, 2015)

The road conditions can be detected using the normalized specular reflectance (to dry road conditions) output of the detectors, as shown in Figure 12:

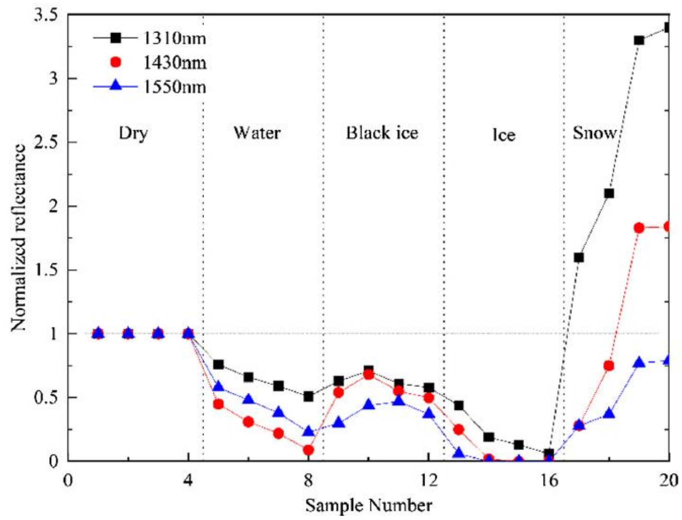

Figure 12: Normalized Reflectance of Road Conditions (Source: MA, 2020)

- Thermal/Hyperspectral and Visible Camera Modules:
  The thermal/hyperspectral cameras consist of a FLIR SC7000 series from FLIR and Specim Hyperspectral systems with multiple detectors to capture images of specific wavelengths and an NVidia Jetson, compatible visible spectrum camera. Each image is first labeled as dry or wet compared with the normalized specular reflectance measurements obtained using the tri-wavelength module. The dry, wet, ice, snow, and black ice areas are identified on the asphalt module and replicated in each image using the tri-wavelength module measurements.

6.8 Develop a hardware prototype to be mounted on a Snowplow for detecting black ice. (EECS)

In the second research task, a hardware prototype is developed to be mounted on a snowplow to detect black ice and communicate via WiFi or satellite networks with real-time warning systems. The reflectance of the NIR radiation and the operation of the hardware prototype mounted on a snowplow during day and night are shown in Figures 13 and 14.

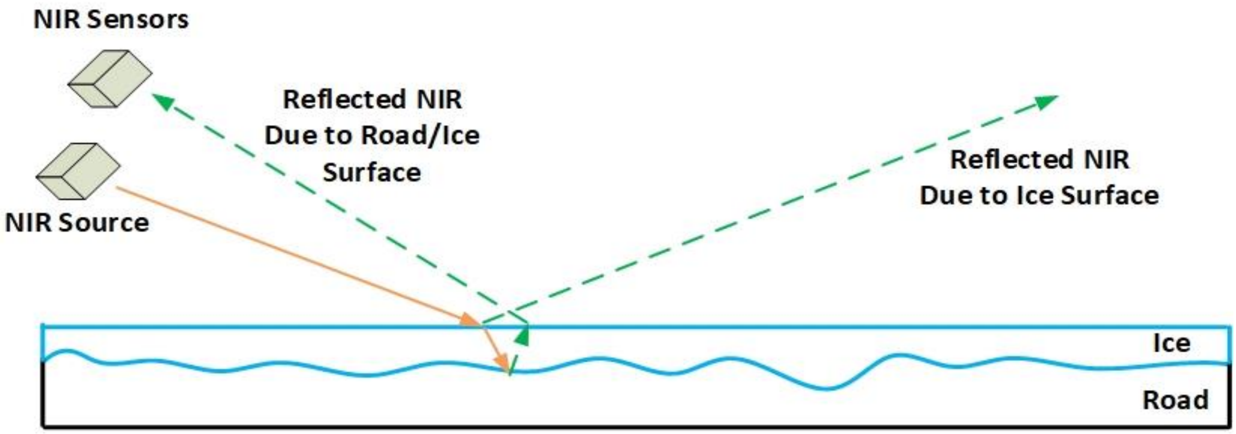

Figure 13: NIR Reflection due to black ice

In Figure 13, the NIR reflection due to the presence of black ice over asphalt is shown. Due to the reflection towards the NIR source because of black ice, the NIR sensors can be mounted close to the NIR source. Hence, a NIR source such as a halogen lamp along with NIR sensors can be mounted at the front end of a snowplow as shown in Figure 14.

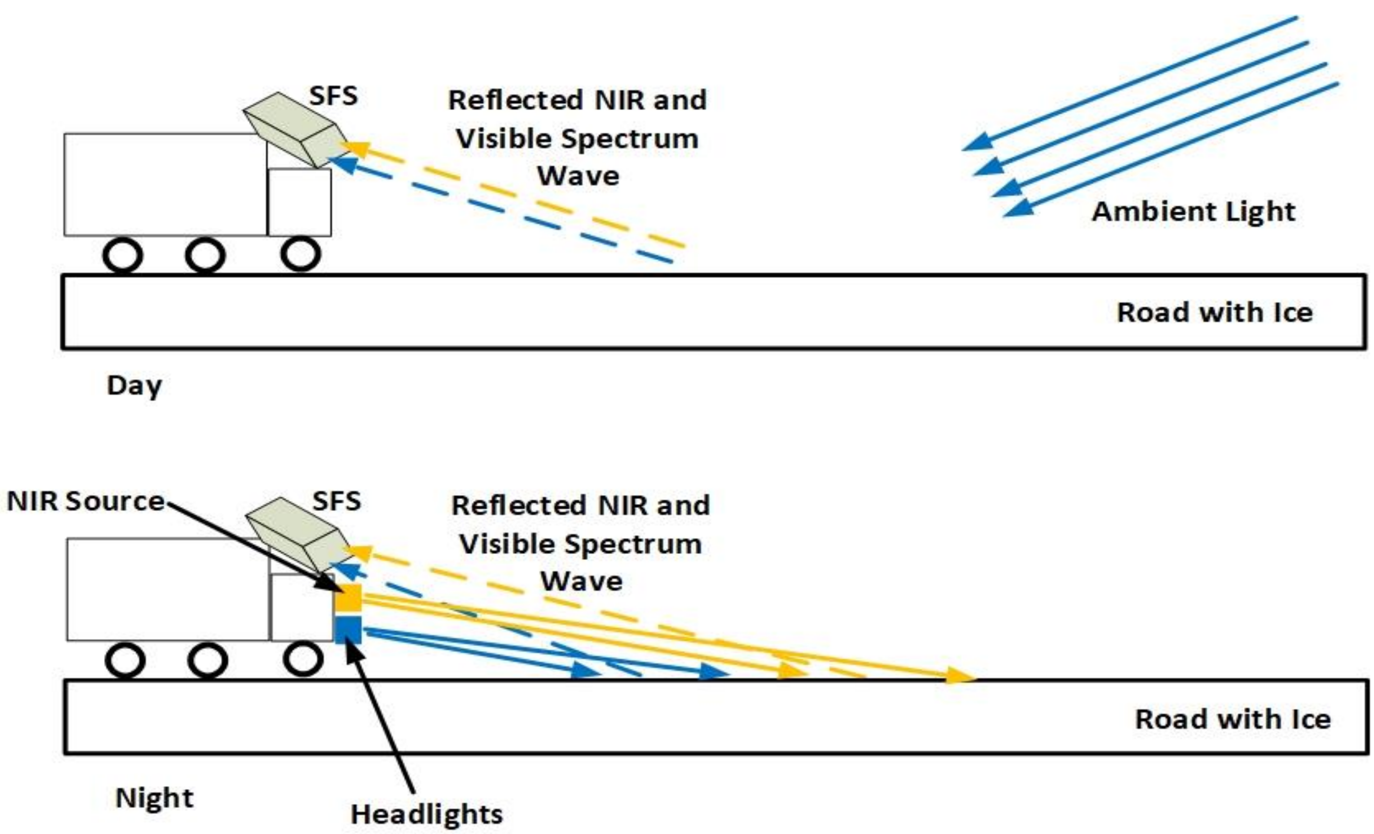

Figure 14: Black ice detection during daylight and night conditions

The thermal/hyperspectral and visible spectrum cameras and the humidity/temperature sensor modules are interfaced with the NVidia Xavier embedded computer. The Xavier computer transmits warning messages with road condition information using cellular or satellite communications to a central location from where the information can be relayed to consumer vehicle navigation instruments. A schematic diagram of the prototype is shown in Figure 15.

Figure 15: Hardware Prototype Schematic

The prototype can be calibrated considering the different adverse weather conditions, such as low visibility, blowing snow, etc.

6.9 Conduct a field test for the developed prototype to evaluate its effectiveness. (EECS)

The experimental black ice testbed laboratory setup is also used for field testing the developed prototype. The tri-wavelength sensor module normalized specular reflectance measurements are used as the ground truth to measure the performance of the machine learning models using the thermal/hyperspectral and visible spectrum camera images. The probability outputs explain the machine learning model's false positive and negative outputs, providing the user with a confidence measure.

6.10 Correlate the black ice data with atmospheric conditions

The roadside sensors can provide a higher prediction accuracy of black ice considering pavement surface conditions on roads. However, the roadside tools tend to possess limited discrete data on specific locations. A more continuous detection systems of black ice is recommended on road networks, especially forecasting black ice on pavement surfaces is limited. The late vehicle models can provide a continuous real-time data of atmospheric conditions using mounted temperature sensors. The spatial data of vehicles can be integrated with the roadside black ice detectors to find a correlation between atmospheric conditions and the possibility of black ice existence.

This task will focus on the methodologies recommended for such correlations. A case study will correlate the data of black ice at slick locations with some atmospheric parameters. WYDOT is reporting sections of slick roads due to black ice. In addition, WYDOT's major highways are equipped with roadside atmospheric sensors to measure important parameters, including air temperatures, wind speed, among other parameters. These datasets will be received from WYDOT to apply the appropriate calibration and correlation analysis to link between atmospheric conditions and the possibility of having black ice. The results will show the techniques that can be applied to future vehicle to infrastructure (V2I) communications to synchronize the black-ice data considering both roadside sensors and in-vehicle atmospheric data. Such an integration will develop a continuous real-time black ice data for decision making.

6.11 Propose the ITS data capture and management for WYDOT

The proposed onsite infrared detectors and in-vehicle detectors will have the ability to detect slipper road sections. Such data is critical to provide warnings to road users. The flow of information starts from the detectors to the service provider who can spread the information using real-time warning systems on roads. The service provider can also deliver the slippery conditions to road authorities for immediate restorative actions on these sections. The slipperiness conditions can be showed in real-time maps on WYDOT road condition applications which will be available to road users.

In this task, the means of data capture and sharing will be described showing the pros and cons of the different strategies. A high-level overview of the current strategies will identify how the black ice data will be collected, stored, and shared using the fixed roadside sensors and in-vehicle sensors.

6.12 Evaluate the forms of warning systems recommended for road users.

Some smart vehicles provide in-car warning systems to warn drivers of possible ice on roads. However, such systems are limited to only late car models. The integration between cars and the infrastructure data sharing is limited. The warning systems can adopt several practices to notify all roadway drivers about the black ice information. Such practices include smart signing warning messages, cell phone or email messages, and real-time interactive maps on WYDOT's road condition reporting applications. Users approaching these sections can receive early warnings and consider precautions to reduce the slipperiness risk.

This task will describe the best form of warning systems recommended considering vehicle-to-vehicle and vehicle-to-infrastructure interactions. In addition, important precautions will be studied for road users, especially in locations exhibiting high skidding-related crash rates and hot spots. The triggers for road closures and warning systems will be studied in this task. In addition, the preference of utilizing some of these practices will be evaluated using survey questionnaires.

7 DELIVERABLES

The deliverables of this research, to be provided to WYDOT are listed as follows:

1. Wyoming specific Safety Performance Function (SPF) in identifying factors affecting black ice related crashes and thus improve safety.
2. Advanced statistical models to minimize the severity of black ice related crashes.
3. Heat maps to identify back-ice related hotspot locations and prioritize treatments.
4. Final prototype fully developed and equipped with sensors, thermal/hyperspectral cameras, and other ITS technologies.
5. A manual describing how to set up the advanced prototype, conduct field experiments, and interpret results.
6. Final report documenting all study tasks and previous literature review to the development of the prototype and its testing.

7. A full-blown implementation plan by the end of the study.

8 TIMELINE

This study is expected to be completed in 30 months which will include conducting the laboratory and field testings.

9 BUDGET

Table 1 summarizes the budget of this study.

Table 1. Study Budget.

Categories	WYDOT
Faculty Salaries	$32,000
Staff	$17,500
Fringe Benefits:Faculty(40.9%)/Staff (50.9%)	$21,996
Student Salaries	$43,000
Student Fringe Benefits (1.8%)	$774
Total Personnel Salaries	$92,500
Total Fringe Benefits	$22,770
TOTAL Salaries & Fringe Benefits	**$115,270**
Travel	$6,000
Equipment	$76,000
Supplies	$4,000
Contractual	
Construction	
Other Direct Costs (Specify)*	$19,000
TOTAL Direct Costs	**$220,270**
F&A (Indirect) Costs	$44,054
TOTAL COSTS	**$264,323**

*Other Direct Cost includes Graduate Student Tuition, Fees and Insurance

REFERENCES

Abdalla, Y. E., Iqbal, M. T., Shehata, M. (2017). Black Ice detection system using Kinect. In *Proceedings of the IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE)*, Windsor, ON, Canada, pp. 1–4.

Alimasi, N., Takahashi, S., Enomoto, H. (2012). Development of a mobile optical system to detect road-freezing conditions. *Bull. Glaciol. Res.,* 30, 41–51.

Chang, J. S.-T., and Fanning, J. J. (1998). Method and apparatus for detecting a road pavement surface condition, U.S. Patent 5 852 243.

Chen, Y. (1991). The use of image analysis for black ice detection, Technical Report.

Cheng, W. and Washington, S. (2008). New criteria for evaluating methods of identifying hot spots. *Transportation Research Record*, *2083*(1), pp.76-85.

Domela, L. (2013). *System automatically detects black ice on roads in real time*. Electronic Engineering. https://www.eejournal.com/fresh_bytes/system-automatically-detects-black-ice-on-roads-in-real-time/. Accessed by March 8, 2022.

FHWA. (2020). How do weather events impact roads? Available: http://ops.fhwa.dot.gov/weather/q1_roadimpact.htm

Gailius, D., and Jačenas, S. (2007). Ice detection on a road by analyzing tire to road friction ultrasonic noise, *Ultragarsas*, vol. 62, no. 2, pp. 17–20.

Haq, M.T., Zlatkovic, M. and Ksaibati, K. (2020). Assessment of tire failure related crashes and injury severity on a mountainous freeway: Bayesian binary logit approach. *Accident Analysis & Prevention*, *145*, p.105693.

Holzwarth, F., and Eichhorn, U. (1993). Non-contact sensors for road conditions, *Sens. Actuat. A: Phys.*, vol. 7, pp. 121–127.

Jonsson, P. Surface Status Classification, Utilizing Image Sensor Technology and Computer Models, Mid Sweden University, 2015.

Lebreton, P. (2018). *Heavy traffic to produce slipperiness data for road users*. Global Security Mag. https://www.globalsecuritymag.fr/Heavy-traffic-to-produce,20180123,76417.html. Accessed by March 8, 2022.

Lee, H., Kang, M., Song, J., and Hwang, K. (2020). The Detection of Black Ice Accidents for Preventative Automated Vehicles Using Convolutional Neural Networks. *Electronics*. doi:10.3390/electronics9122178

Liu, T., Pan, Q., Sanchez, J., Sun, S., Wang, N., and Yu, H. (2017). Prototype Decision Support System for Black Ice Detection and Road Closure Control. *IEEE Intelligent Transportation Systems Magazine*. DOI: 10.1109/MITS.2017.2666587

Liu, T., Wang, N., Yu, H., Basara, J., (Eric) Hong, Y., and Bukka patnam, S. (2014). Black Ice Detection and Road Closure Control System for Oklahoma. Technical Report, FHWA-OK-14-08, Oklahoma Department of Transportation.

Live Storms Media. (2021). 04-06-2021 Midwest, WY - Spring Snow on Interstate 25. Available: https://www.youtube.com/watch?v=y3ry2UbqE8c

Ma, X., Ruan, C. (2020). Method for black ice detection on roads using tri-wavelength backscattering measurements. *Appl. Opt.*, 59, 7242–7246.

Minullin, R. G., Mustafin, R. G., Piskovatskii, Y. V., Vedernikov, S. G., Lavrent'ev, I. S. (2011). A detection technique for black ice and frost depositions on wires of a power transmission line by location sounding. *Russ. Electr. Eng.*, 82, 541–543.

Roadside Linguistics – Sign Syntax. (2012), A Walk in the Words. Available: http://walkinthewords.blogspot.com/2012/05/roadside-linguistics-sign-syntax.html

Roy, U.; Farid, A.; and and Ksaibati, K. (2022), Effects of Pavement Friction and Geometry on Traffic Crashes: A Case Study in Wyoming. Submitted to *International Journal of Pavement Research and Technology*. Under Review

Shimadzu_Corporation," The Structure of a Spectrophotometer," March 11, 2015

Stolarczyk, L. G., and Stolarczyk, G. L. (1997). Apparatus and method for the detection and measurement of liquid water and ice layers on the surfaces of solid materials, U.S. Patent 5 686 841.

Survo, P., and Haavasoja, T. (1998). Method and apparatus for measuring road surface conditions, U.S. Patent 5 801 647.

Tabatabai, H., Aljuboori, M. (2017). A novel concrete-based sensor for detection of ice and water on roads and bridges. *Sensors,* 17, 2912.

Trevino, M., Dossey, T., Yildirim, Y., Barrett, M., Shaw, C.,Ongel, A., Kohler, E., Lu, Q., Wang, H., and Flintsch, G. (2007). Black ice detection in open graded friction courses, in Proc. TRB Annu. Meeting, Washington D.C.

Washington, S.P. and Cheng, W., (2005). *High risk crash analysis* (No. FHWA-AZ-05-558). Arizona. Department of Transportation.

WCNC Charlotte. (2022). What to do if you hit black ice on the roads. Available: https://www.wcnc.com/article/news/local/connect-the-dots/what-to-do-if-you-hit-black-ice-on-the-roads/275-0a5a17ba-c265-435a-abcf-1c7024c9c49c