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BLACK ICE PREDICTION MODEL FOR ROAD PAVEMENT USING WEATHER FORECAST DATA AND GIS DATABASE

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Abstract. Black ice is a thin coating of ice on the road surface, which strongly reduces friction at the tire-road surface, resulting in dangerous driving when it happens. An appropriate diagnostic of black ice could prevent traffic accidents as well as provide timely notice to drivers. Therefore, this study aims at developing a black ice prediction model to diagnose the probability of black ice formation. Several combinations that can form road ice have been considered, including freezing rain, hoar frost, freezing of wet roads. In addition, black ice risky index (BRI) has been computed to reflect the probability of black ice formation. To acquire a fast prediction and high accuracy, the existing Geographical Information System (GIS) database and meteorological data have been utilized. GIS database includes road geometry and location of automatic weather stations, while the meteoritical data consists of air temperature, wind speed, humidity, cloud cover. The model has been developed based on the Python programming language. A 5-km road condition was observed from 1 December to 31 December 2021 to determine the model accuracy. Based on

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the results from the prediction model, black ice formation has been verified when the BRI is higher than 0.8. The model may be useful to develop black ice diagnostic program.

Keywords: API, asphalt pavement, black ice, GIS, meteorological data, prediction model.

Introduction

Black ice happens when a thin coating of ice is formed on the road surface. It is difficult to recognize due to its transparent property. Once it happens, black ice strongly reduces the friction of tire-road and road surface, thus resulting in dangerous driving (Minh Phan et al., 2021). According to Korea Express Corporation, a black ice road is 6 and 14 times more slippery than a snowy road and normal condition road, respectively. From 2014 to 2018, there were 706 deaths due to accidents caused by black ice in South Korea. This number was approximately four times higher than death caused by snow (Kim Hyun-bin, 2019). Several technologies have been developed to reduce the hazard of ice (Gode & Paeglitis, 2014; Zilioniene & Laurinavicius, 2007). For example, embedded heat wires under roads can melt ice when it occurs. However, installation cost, maintenance, and electricity power consumption would be huge. A report from the local authority showed that there was approximately $4 million to install a 5–km wired road (Kim Hyun-bin, 2019). Another technology is using road salt, which could prevent the formation of ice on the road surface (Szklarek et al., 2022). Nevertheless, the road salt could deteriorate pavement performances as well as affect the surrounding environment. So far, the utilization of latent heat fusion of phase change material to delay black ice formation (Minh Phan et al., 2021) as well as speed up ice thawing (Souayfane et al., 2016). Consequently, the diagnosis of black ice is considered an effective solution. Road ice prediction is a hot topic that attracted many researchers. An appropriate prediction could help drivers be attentive while driving or choose other routes. In addition, prediction also provides a fast and effective response to prevent traffic accidents.

Theoretically, the road requires freezing temperatures (below 0 °C) and moisture conditions at the surface to form ice. Hence, several combinations have been proposed to predict black ice formation such as freezing rain, hoar frost, and freezing of wet surface (Mass & Steed, n.d.). Freezing rain is rain that falls in liquid form but freezes upon impact and forms a coating of ice on the surface. The diagnostic of freezing rain based on the scheme has been reported in Ramer’s study (Ramer, 1993). In Ramer’s study, a wet-bulb temperature profile was used to predict precipitation types, including freezing, rain, snow, and ice pellet. Barszcz et al. used a numerical weather prediction model to predict freezing rain (Barszcz et al., 2018). Hoar frost is water vapor sublimating on the road surface when the temperature is below zero and the dew point temperature is higher than the road surface temperature (Karlsson, 2001). As reported in Gocheva's research, wind speed, air temperature, and humidity are considered important factors that affect a hoar frost phenomenon (Gocheva, 1990). The temperature difference between road surface temperature and dew point temperature could impress the amount of hoar frost (Gustavsson & Bogren, 1990). Another condition that forms road ice is surface temperatures that are higher than 0 °C during the daytime but drop below freezing at the night-time when the road surface is wet. The wet condition of the road can be caused by light snow or light rain. Once snow drops to the road surface, it melts, causing the wet condition. This condition may form road ice in the nighttime or the early morning. The freezing of wet roads has been reported in Lim and Kim's research (Lim & Kim, 2020).

Nowadays, Geographic Information System (GIS) is used in various fields and technologies, such as transport, logistics, engineering. GIS is known as a system that creates, manages, analyses, and maps all types of data, including the road map, river, bridges, water ground (Wikipedia, 2022). GIS database is beneficial to manage as well as analyse geographic data. In recent years, the utilization of GIS database in research is more popular; for example, the research conducted by Hong et al. estimated locations of road icing using GIS (Hong et al., 2021). Liu et al. used a spatial database to develop a diagnostic of road closure under emergencies (Liu et al., 2014). Besides, with the rapid advent of the cloud service industry, API (Application Program Interface) has inspired the development of large-scale service and fast attempts. Through API, the data can be fast and automatically accessed. In addition, using API also reduces the pressure on hardware problems such as memory and processors. Therefore, using API to obtain meteorological data may be beneficial in quick diagnostics and fast response to emergency cases.

This study aimed at developing a black ice prediction model using a geographic information system database and meteorological data. The model was constructed based on several combinations that form black ice, including freezing rain, hoar frost, freezing of wet surface (due to light snow or light rain). The priority purpose of the model is to diagnose the probability of black ice formation at a specific road. Therefore, road spatial was used to improve the prediction scale of the model while meteorological data were obtained throughout the API service. The model was developed based on the Python programming language. To reflect the probability of black ice formation, the black ice risky index

(BRI) was developed. In order to validate the accuracy of the model, a 5-km road in Gunsan city, Jeollabuk, South Korea, was monitored from 1 December 2021 to 31 December 2021. The road condition was observed at 8:00 and 22:00 every day. Finally, prediction and real-time observation were compared to determine the model accuracy. The findings of this study may be beneficial in the development of black ice prediction program.

1. Model development

As illustrated in Figure 1, several combinations were considered to develop a prediction model. The weather condition was first diagnosed based on the meteorological data from KMA (Korea Meteorological Administration, 2022). In the dry condition case, the road surface

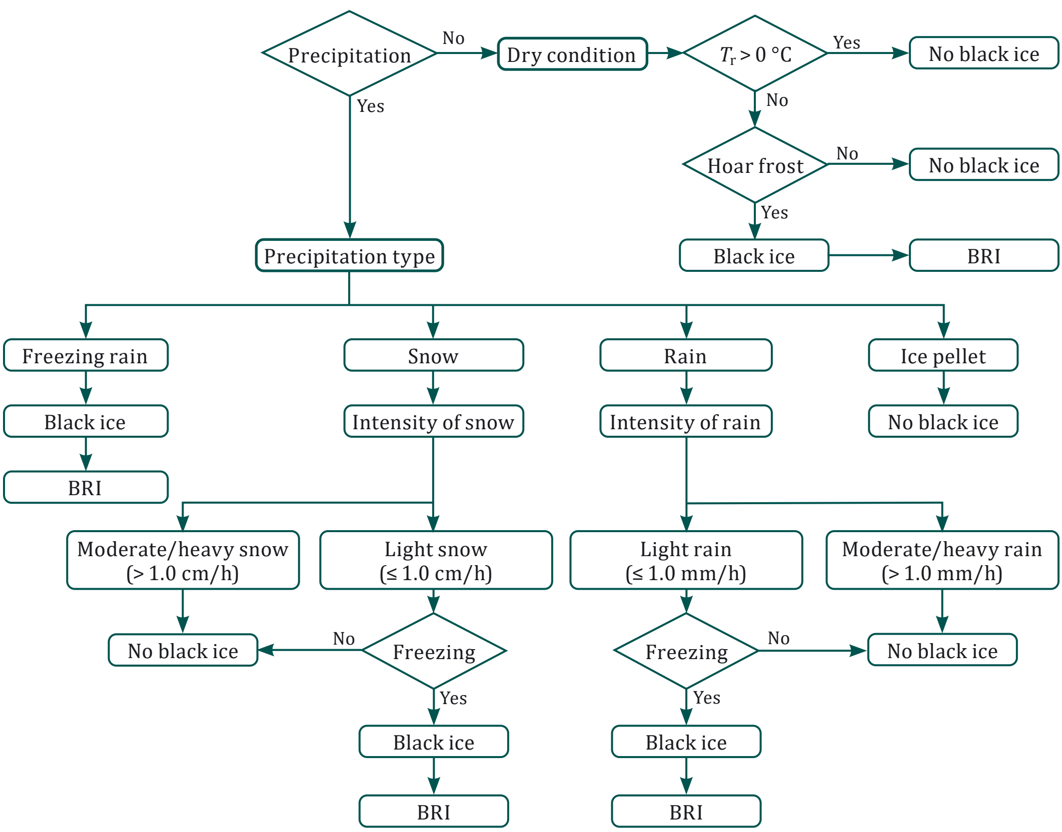

Figure 1. Algorithm of black ice prediction model

temperature was then considered to determine black ice formation. If the road surface temperature was higher than 0 °C, there was no black ice observation. However, when road surface temperature was lower than 0 °C, the hoar frost phenomenon was considered. In the precipitation case, several precipitation types were considered, including freezing, snow, rain, and ice pellet. In this study, ice pellet precipitation as well as moderate and heavy snow were not accounted to the prediction model. This is because high intensity of snowing may cause snow slush rather than black ice. The light snow, where the snow acummulation was less than 1.0 cm per hour, was considered a reason causing black ice. Similary, the light rain (e.g. < 1.0 mm/hr) was only accounted as a condition forming black ice. Therefore, a total of three precipitation types was used to predict black ice. At the end of each precipitation prediction process, the black ice risky index (*BRI*) was calculated. Black ice risky index is defined as the probability of black ice happening, where 0 stands for no black ice phenomenon and 1.0 is black ice formation. *BRI* may be beneficial in the warning system.

1.1. Black ice caused by hoar frost

Hoar frost is water vapor sublimating on the road surface when the temperature is below zero and the dew point temperature is higher than the road surface (Karlsson, 2001). Hoar frost also commonly forms on the road surface when the road surface cools more quickly than the air layer above. As displayed in Figure 2, wind speed, road surface temperature (T_r) and dew point (T_d) are the three main factors that affect the hoar frost phenomenon. When wind speed was higher

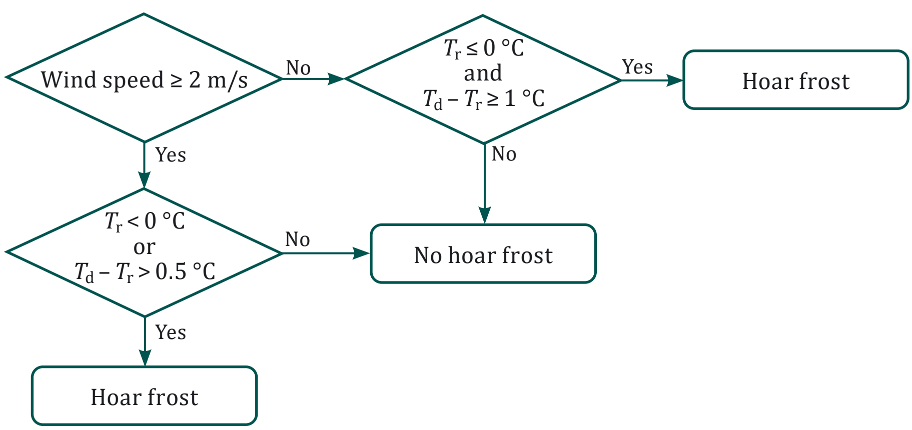

Figure 2. Black ice caused by hoar frost

than 2 m/s, hoar frost was confirmed when road surface temperature was lower than 0 °C and the temperature difference of road surface temperature and the dew point was greater than 1.0 °C. In contrast, when wind speed was smaller than 2 m/s, if road surface temperature was lower than 0 °C or temperature difference of road surface temperature and the dew point was higher than 0.5 °C, hoar frost was confirmed (Toms et al., 2017). In addition, cloud cover was accounted into a model. The clear sky promotes rapid cooling (Mass & Steed, n.d.). Therefore, cloud cover was considered a factor affecting a black ice risky index.

1.2. Black ice caused by freezing rain

Freezing rain is defined as the rain that freezes when in contact with the solid surface; therefore, freezing rain is one of the reasons that causes black ice. In this study, the Ramer scheme (Figure 3), which has been widely used in freezing rain forecasting, is used to diagnose freezing rain (Ramer, 1993). The wet-bulb temperature profile was assigned to determine this precipitation. The wet-bulb temperature is calculated as shown in Equation (1). As shown in Figure 3, freezing

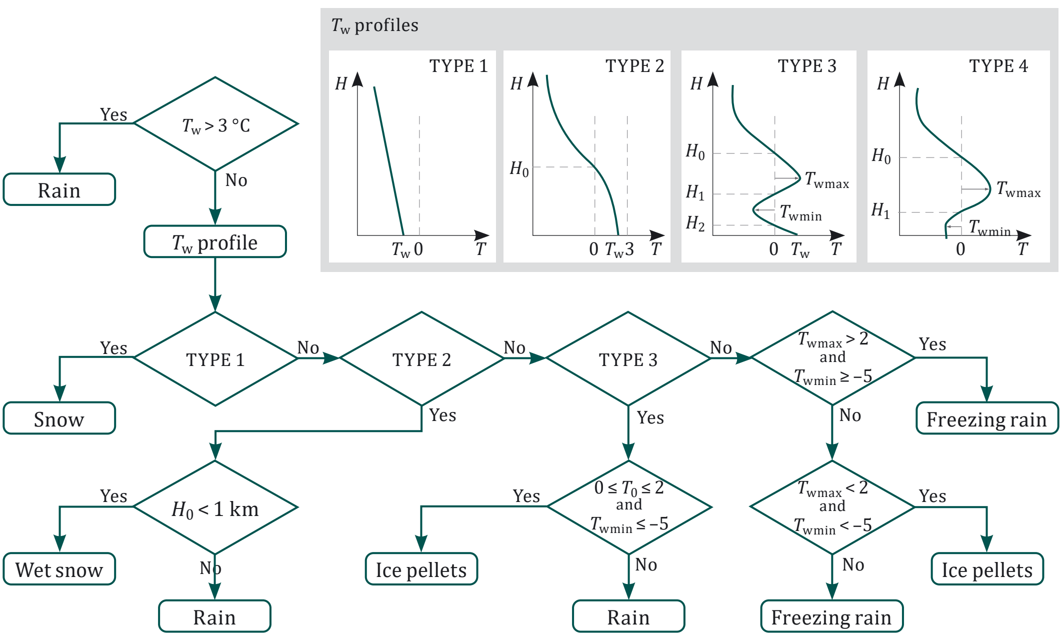

Figure 3. Prediction of freezing rain using Ramer scheme rain occurs when the wet-bulb temperature profile falls into Type 3. In the profile of Type 3, the wet-bulb temeprature is lower than 0 °C when the high is greater than H_0, and higher than 0 °C when the height is in the range of H_0 and H_1, and the temperature is lower than 0 °C when the height is in the range of H_1 and H_2.

$$T_w = T \times \left[0.151977(RH + 8.313659)^{1/9}\right] + \arctan(T + RH) - \arctan(RH - 1.676331) + 0.00391838RH^{3/2} \times \arctan(0.023101 \times RH) - 4.686035 \quad ,(1)$$

where T_w is wet-bulb temperature, °C, T is air temperature, °C, and RH is relative humidity, %.

Due to KMA only providing data of seven upper-air observations throughout South Korea, there was an overestimate if only using these data to predict freezing rain. Therefore, the black ice risky (*BRI*) was developed to determine the probability of black ice formation. Based on the previous studies in South Korea, four main factors affect black ice formation, including temperature, wind speed, humidity, and road surface temperature (Lim & Kim, 2020). These data could be obtained from KMA as mentioned in the previous section. The *BRI* calculation is shown in Equation (2). When the freezing rain was confirmed, the initial *BRI* was assigned 0.5. Then, four conditions were assumed to compute the black ice risky index. When each condition was met, the *BRI* accumulated 0.125. In contrast, when there was no freezing rain, the *BRI* equalled zero.

$$BRI = BRI_{\text{inital}} + BRI_{\text{humidity}} + BRI_{\text{windspeed}} + BRI_{T_a} + BRI_{T_r}, \quad (2)$$

where

BRI is a black ice risky index;

$BRI_{\text{initial}} = 0.5$ if freezing rain else $BRI = 0$;

$BRI_{\text{humidity}} = 0.125$ if humidity > 65% else $BRI_{\text{humidity}} = 0$;

$BRI_{\text{windspeed}} = 0.125$ if wind speed < 3 m/s else $BRI_{\text{windspeed}} = 0$;

$BRI_{\text{Ta}} = 0.125$ if $T_a < 3$ °C else $BRI_{\text{Ta}} = 0$;

$BRI_{\text{Tr}} = 0.125$ if $T_r < 0$ °C else $BRI_{\text{Tr}} = 0$.

1.3. Black ice caused by freezing wet road

When snow happened, its intensity was determined. The snow intensity consists of three levels: light snow (lower than 1.0 cm), moderate snow (from 1.0 to 5.0 cm), and heavy snow (higher than 5.0 cm). Light snow may cause the chance of freezing of melting snow – the high potential of black ice formation. Moderate and heavy snow laed to snow-slush, which may not cause black ice. Therefore, light snow and freezing melting snow were considered in the study. When snow drops on the road surface, it melts, leading to the wet condition of the road surface. Under low air temperature and wind speed, ice can be formed on the road surface.

Moderate and heavy rain may not cause black ice formation while light rain leads to the wet road, which causes black ice formation. There are four levels of rain: Level 1: 0.1–1 mm, Level 2: 1–30.0 mm, Level 3: 30.0–50.0 mm, Level 4: higher than 50 mm. Level 1 was used to predict black ice formation. In the current study, snow and rain were diagnosed by KMA. The prediction of precipitation and the amount of precipitation were obtained from KMA. The model of freezing of wet road can be summarised as shown in Figure 4 (Lim & Kim, 2020).

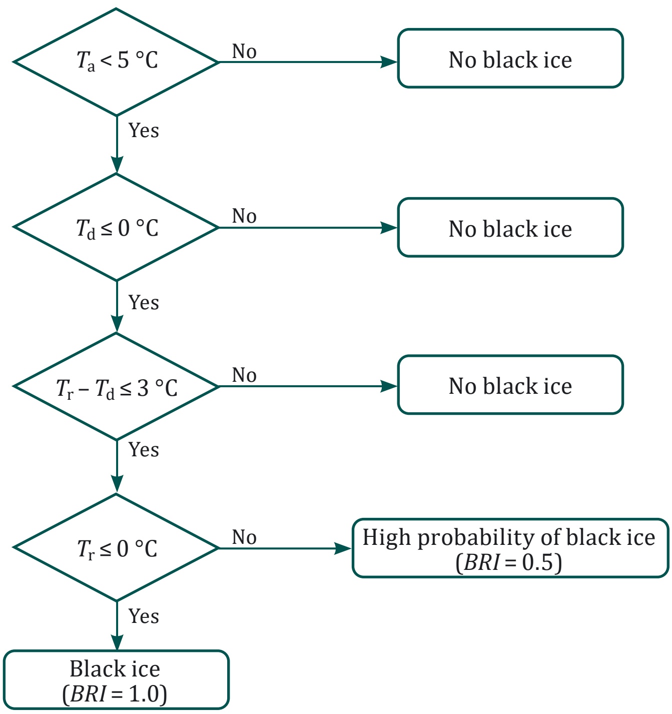

Figure 4. Black ice caused by freezing of wet road

2. Data preparation

2.1. Meteorological data and GIS data

As mentioned in the previous section, the meteorological data used in this study was provided by Korea Meteorological Association through API. To predict freezing rain, the vertical upper-air temperatures were obtained from seven upper-air observations as shown in Figure 5a. Upper-air data consists of air temperature and relative humidity involved air pressure. These data were diagnosed with the interval of 12 hours. Meanwhile, the weather data of spatial roads were obtained from automatic weather stations (AWS). There are over 200 automatic weather stations in South Korea as displayed in Figure 5b. The spatial

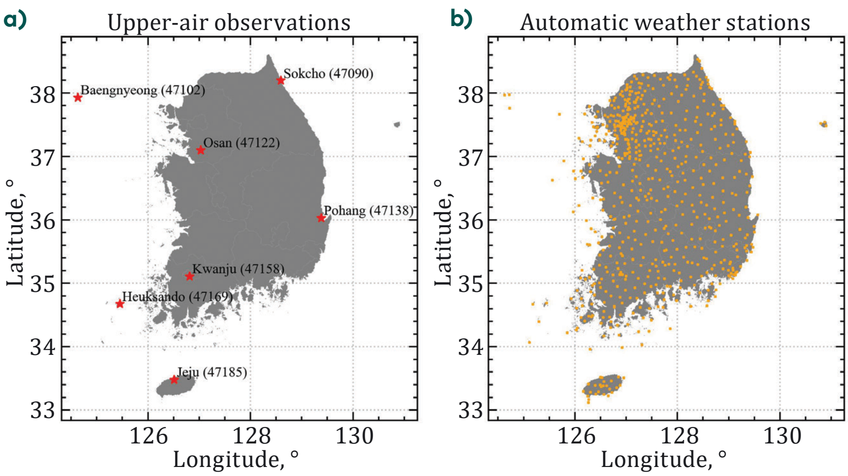

Figure 5. Distribution of upper-air observation and automatic weather station in South Korea

	osm_id	code	fclass	name	ref	oneway	maxspeed	layer	bridge	tunnel	geometry
0	22799949	5112	trunk	?????	21	F	0	0	F	F	LINESTRING (126.77450 35.94183, 126.77158 35.9...
1	22801216	5113	primary	???	26	B	0	0	F	F	LINESTRING (126.65699 35.95681, 126.65692 35.9...
2	32902548	5112	trunk	None	29	F	0	0	F	F	LINESTRING (126.80796 35.93727, 126.80910 35.9...
3	32902633	5132	trunk_link	None	None	F	0	0	F	F	LINESTRING (126.81586 35.93024, 126.81572 35.9...
4	34992837	5114	secondary	?????	711;744	B	0	0	F	F	LINESTRING (126.81396 35.94483, 126.81709 35.9...
...	...	...	...	...	...	...	...	...	...	...	...
5874	934908830	5141	service	None	None	B	0	-1	F	T	LINESTRING (126.70511 35.96192, 126.70539 35.9...
5875	934908831	5141	service	None	None	B	0	0	F	F	LINESTRING (126.70539 35.96186, 126.70548 35.9...
5876	934908832	5141	service	None	None	B	0	0	F	F	LINESTRING (126.70443 35.96202, 126.70435 35.9...
5877	934908833	5141	service	None	None	B	0	0	F	F	LINESTRING (126.70429 35.96182, 126.70440 35.9...
5878	942097564	5113	primary	None	None	B	0	0	F	F	LINESTRING (126.58763 35.94736, 126.58761 35.9...

5879 rows × 11 columns

Figure 6. A capture of spatial road data

weather data include air temperature (T_a), wind speed (W), relative humidity (RH), cloud condition (C), and dew point (T_d). The KMA provides the forecast data in the next four hours. Both upper-air data and spatial data were accessed through API provided by Public Data Portal (Public Data Portal, 2022).

As this study aimed to predict the probability of black ice formation up to road scale, the spatial of roads was considered. As shown in Figure 6, these data include road identification, road classification, bridge or tunnel in the road, and geometry. The data were provided by the National Spatial Data Infrastructure (NSDI, 2022). For calculating the black ice risky index, a featured point, which was the beginning of the road segment, was extracted from every road segment.

2.2. Road surface temperature

In this study, road surface temperature was obtained from automatic weather stations. Due to the surface temperature being the main factor that directly affects the formation of black ice, an asphalt concrete slab was prepared to measure the road surface temperature under real-time conditions. As shown in Figure 7, two thermocouples were embedded in the asphalt slab. One is on the surface, and another is 1 cm below the surface. The surface temperature was recorded during the observation time.

Figure 7. Measurement of surface temperature

3. Improving prediction scale

The geographic information system database provides the geometry of each road segment, as shown in Figure 7. Because the length of each road segment was shorter than the length of the road, the beginning point was selected as a representative of this road segment. In addition, the weather data were only available at automatic weather stations. Therefore, the black ice risky index of the road is calculated based on the triangle interpolation method. This method was to improve or interpolate meteorological data at a specific location (Liu et al., 2014). The improving prediction scale includes two steps. Firstly, the beginning points were assigned to the BRI of AWS based on the nearest neighbour algorithm as shown in Figure 8a. The values were computed based on

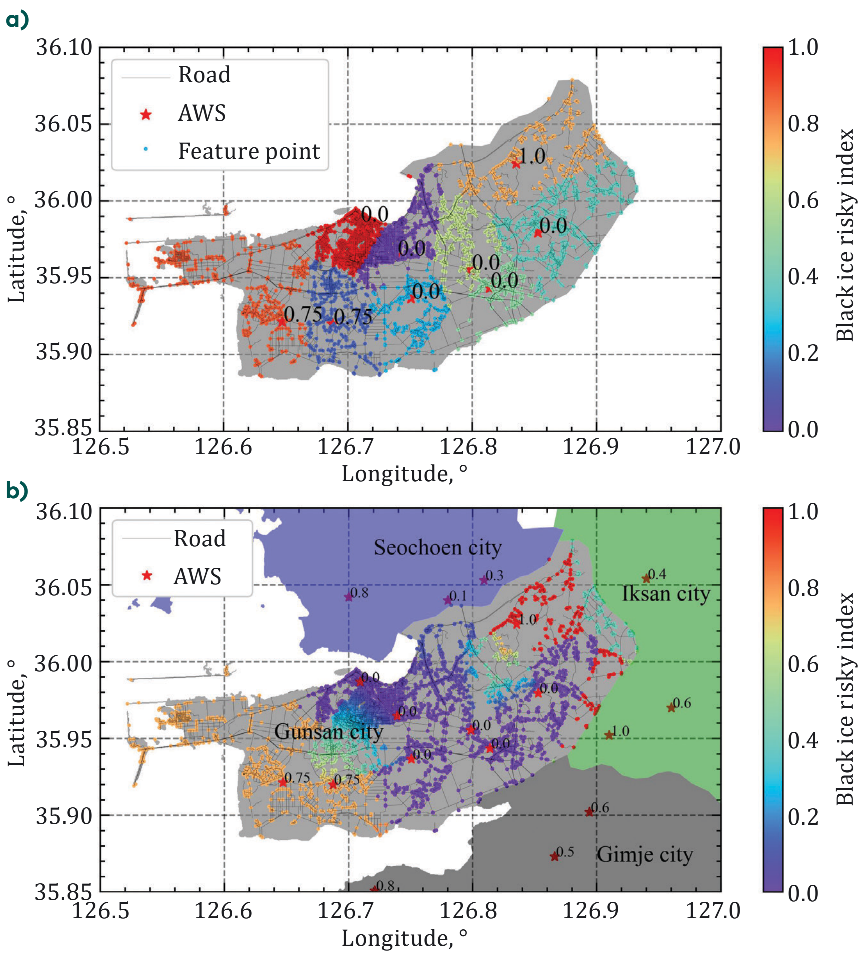

Figure 8. Nearest neighbour and triangle interpolation algorithm

the distance from the beginning point to the nearest AWS. Secondly, the BRI of beginning points located inside the AWS triangle were again computed by the triangle interpolation method as displayed in Figure 8b.

The triangle interpolation algorithm can be explained as a black ice risky index of a point *P* (longitude, latitude), which was calculated based on three vertices of the triangle containing the point *P* as shown in Figure 9. The interpolated BRI was calculated as shown in Equation (2). The contributed weight to point *P* was computed using Equation (3). The contributed weight was related to the distance from point *P* to three vertices containing point *P*.

$$BRI_P = \frac{W_{v1} \times BRI_{v1} + W_{v2} \times BRI_{v2} + W_3 \times BRI_3}{W_{v1} + W_{v2} + W_{v3}}, \quad (2)$$

where

BRI_{v1}, BRI_{v2}, BRI_{v3} are a black ice risky index at point v1, v2, v3, respectively;

W_{v1}, W_{v2}, W_{v3} are the contributed weight to point *P*.

The contributed weight was calculated using Equation (3).

$$\begin{aligned} W_{v1} &= \frac{1}{D_{v1}};\quad W_{v2} = \frac{1}{D_{v2}};\quad W_{v3} = \frac{1}{D_{v3}} \\ D_{v1} &= \sqrt{\left(\mathrm{Lat}_{v1} - \mathrm{Lat}_P\right)^2 + \left(\mathrm{Lon}_{v1} - \mathrm{Lon}_P\right)^2}, \\ D_{v2} &= \sqrt{\left(\mathrm{Lat}_{v2} - \mathrm{Lat}_P\right)^2 + \left(\mathrm{Lon}_{v2} - \mathrm{Lon}_P\right)^2} \\ D_{v3} &= \sqrt{\left(\mathrm{Lat}_{v3} - \mathrm{Lat}_P\right)^2 + \left(\mathrm{Lon}_{v3} - \mathrm{Lon}_P\right)^2} \end{aligned} \quad (3)$$

where

D_{v1}, D_{v2}, D_{v3} are distance from v1, v2, v3 to point *P*, respectively;

Lat_{v1}, Lat_{v2}, Lat_{v3}, Lat_P are latitude of v1, v2, v3, point *P*, respectively;

Lon_{v1}, Lon_{v2}, Lon_{v3}, Lon_P are longitude of v1, v2, v3, point *P*, respectively.

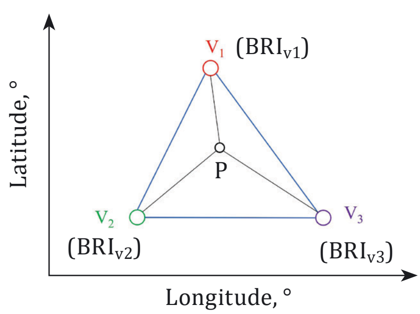

Figure 9. Triangle interpolation method for calculating *BRI*

4. Validation and discussion

As shown in Figure 10, a 5-km road in Gunsan city, Jeollabuk-do, South Korea was observed to validate the model accuracy. The road conditions were monitored from 1 December 2021 to 31 December 2021. Road conditions were observed at 8:00 AM and 10:00 PM every day. At the same time, the surface temperatures from asphalt slab were recorded. The surface temperatures obtained from asphalt slab were used to compare the difference between model and real-time observations.

The black ice prediction results and real-time observations are shown in Figure 11. The diagnostic showed that there were 9 cases, including 6 cases in the early morning (8:00 AM) and 3 cases at night (at 10:00 PM). The real-time observations presented only 6 cases of black ice, including 7 December at 8:00 and 22:00, 8 December at 8:00, 25 December at 8:00 and 22:00, and 27 December at 22:00. As shown in Table 1, there were 4 black ice prediction cases, including 19–21 December at 8:00, and 24 December at 22:00, there were no observations of black ice. The observations only showed two *BRI* values, including 0 and 1. The 0 value stands for no chance of black ice, while 1 represents black ice formation.

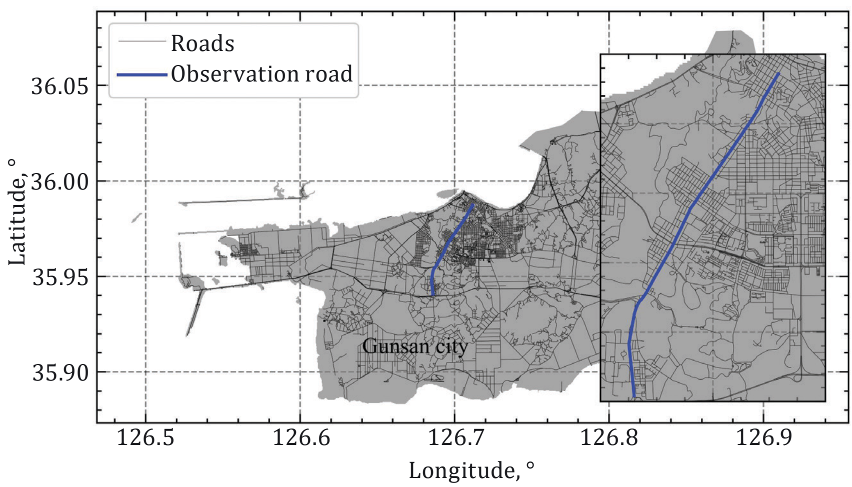

Figure 10. A 5-km observation road in Gunsan city

Table 1. Summary of black ice formation cases

Date Time	T1H	REH	WSD	RN1	SNO	TS0	TS1	SKY	DEW	BRI	OBS
211207_0800	2.7	90	0.1	0	0	1.1	0.0	1	1.2	0.88	1
211207_2200	6.0	73	0.4	0	0	3.3	2.0	1	1.5	0.00	1
211208_0800	2.5	96	0.9	0	0	1.9	0.9	1	1.9	0.88	1
211219_0800	0.8	86	0.9	0.6	0.4	1.7	0.7	3	–1.3	0.50	0
211220_0800	4.8	73	4.2	0	0	3.4	2.4	3	0.4	0.62	0
211221_0800	5.8	92	2.7	0	0	3.7	2.3	1	4.6	0.75	0
211224_0800	0.1	68	5.0	0	0	–0.2	–1.2	3	–5.1	0.75	0
211225_0800	–5.9	63	4.6	0	0	–1.9	–2.9	1	–11.9	1.00	1
211225_2200	–8.0	63	2.8	0	0	–3.4	–4.1	3	–13.9	0.75	1
211227_2200	0.6	79	2.0	0.1	0	0.0	–1.0	3	–2.6	1.00	1

Note: T1H = air temperature, °C; REH = relative humidity, %; WSD = wind speed, m/s; RN1 = rain, mm; SNO, cm; TS0 = predicted road surface temperature, °C; TS1 = measured road surface temperature, °C; SKY = cloud cover (1 = clear sky, 3 = partly cloudy, 4 = cloudy), DEW = dew point, °C; BRI = black ice risky index; OBS = real time observation (1 is black ice, 0 is no black ice)

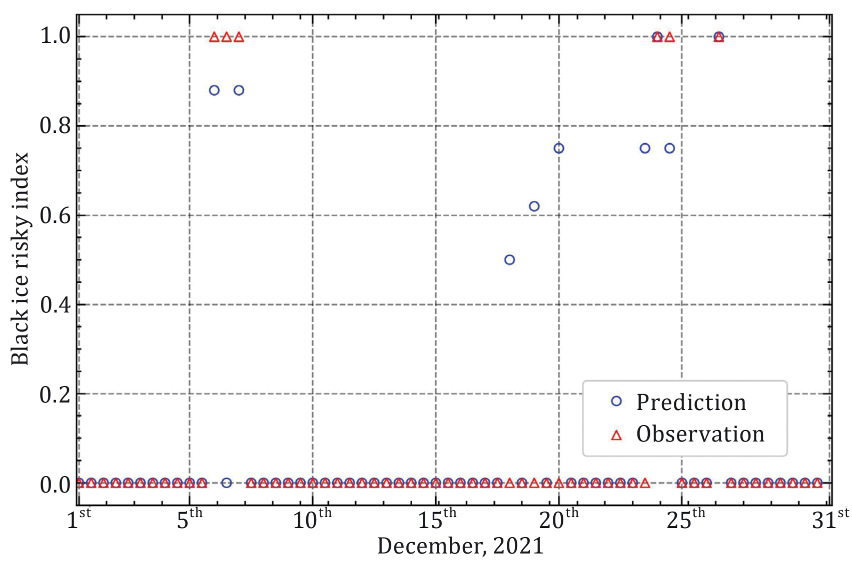

Figure 11. Prediction and observation of black ice

To determine the accuracy of the prediction model, only black ice formation cases were considered. There was assumption that the black ice happened when the probability black ice risky index was higher than 0.5. The accuracy of the model was only 40% (4 correct cases and 6 incorrect cases). This may be because of other factors as vehicles and the surrounding buildings, which could increase surface temperature. The surrounding buildings could absorb solar energy during daytime and emit it during nighttime (Mass, n.d.). However, the model was enhanced up to 70% (7 correct cases and 3 incorrect cases) when increasing *BRI* to 0.8. The higher level of *BRI* for confirming black ice formation could reduce overestimation. Therefore, a *BRI* of 0.8 was selected to diagnose the chance of black ice formation.

As shown in Figure 12a, snow was observed on 19 December at 22:00. Black ice was not observed although the black ice risky index was 0.5. This is because the road surface temperature was higher than 0 °C, which might not freeze the wet road surface. The prediction result on 24 December was 0.75; however, real-time observation showed that there was partly the presence of black ice (Figure 12b). Finally, the black ice formation was confirmed on 27 December at 22:00, as shown in Figure 12c.

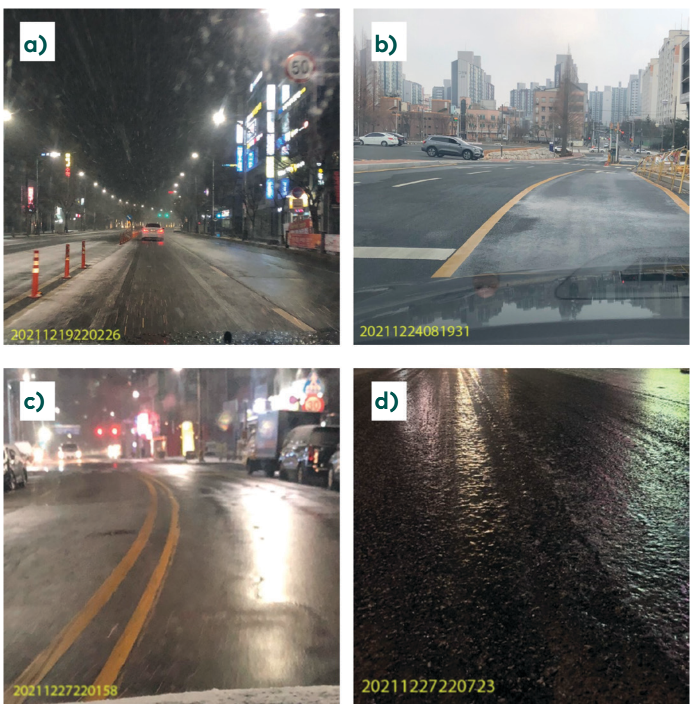

Figure 12. Real-time observations of road condition

Conclusions

The study proposed a model to predict black ice formation based on the Geographical Information System database and meteorological data obtained from Korea Meteorological Administration. Black ice risky index (*BRI*) was computed to reflect the chance of black ice formation. A 5-km road-surface conditions were observed to validate model accuracy. The following key findings can be drawn:

- The black ice prediction model was successfully developed based on freezing rain, hoar frost, freezing wet surface;
- Utilization of GIS and meteorological data through API provided a fast and precise response to emergency cases. The model can diagnose the probability of black ice formation in the next four hours based on the data provided by KMA;
- Validation presented that a *BRI* of 0.8 was an appropriate value to confirm black ice formation. Meanwhile, the *BRI* of 0.5 may be valuable for warning about the chance of black ice formation.

In general, this study provided a method to predict black ice formation based on GIS and meterology data in the next four hours through API Python programign language. However, more analysis on rutting effect, surounding environment, and the location of road (e.g., rural, urban) should be performed in further research.

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REFERENCES

Barszcz, A., Milbrandt, J. A., & Thériault, J. M. (2018). Improving the explicit prediction of freezing rain in a kilometer-scale numerical weather prediction model. *Weather and Forecasting*, *33*(3), 767–782. https://doi.org/10.1175/WAF-D-17-0136.1

Gocheva, A. (1990). Statistical distribution of air temperature, relative humidity and wind velocity during rime-icing for the non-mountain part of the territory of Bulgaria. *Proceedings of 5th International Youth School on Meteorology and Hydrology*, *4*, 84–89.

Gode, K., & Paeglitis, A. (2014). Concrete bridge deterioration caused by de-icing salts in high traffic volume road environment in Latvia. *The Baltic Journal of Road and Bridge Engineering*, *9*(3). https://doi.org/10.3846/bjrbe.2014.25

Gustavsson, T. & Bogren, J. (1990). Road slipperiness during warm air advection. *Meteorological Magazine*, *119*, 267–270.

Hong, S.-B., Lee, B.-W., Kim, C.-H., & Yun, H.-S. (2021). System dynamics modeling for estimating the locations of road Icing using GIS. *Applied Sciences*, *11*(18), Article 8537. https://doi.org/10.3390/app11188537

Karlsson, M. (2001). Prediction of hoar-frost by use of a road weather information system. *Meteorological Applications*, *8*(1), 95–105. https://doi.org/10.1017/S1350482701001086

Kim Hyun-bin. (2019). *Fears of black ice spreads nationwide*. The Korea Times. https://www.koreatimes.co.kr/www/nation/2019/12/281_280755.html

Korea Meteorological Administration. (2022). *KMA*. https://data.kma.go.kr/cmmn/main.do

Lim, H.-S., & Kim, S.-T. (2020). A study on road ice prediction by applying road freezing evaluation model. *Journal of the Korean Applied Science and Technology*, *37*(6), 1507–1516. https://doi.org/10.12925/jkocs.2020.37.6.1507

Liu, T., Wang, N., Yu, H., Basara, J., Hong, Y. (Eric), & Bukkapatnam, S. (2014). *Black ice detection and road closure control system for Oklahoma* (Final Report FHWA-OK-14-08). Oklahoma Department of Transportation. https://l92018.eos-intl.net/elibsql16_L92018_Documents/FHWA-OK-14-08%202249%20Liu.pdf

Mass, C. (n.d.). *Roadway icing and weather: A tutorial*. Washington Road and Weather Page. https://www.atmos.washington.edu/~cliff/Roadway.html

Mass, C., & Steed, R. (n.d.). *Roadway icing and weather: A tutorial*. College of the Environment. https://www.atmos.washington.edu/~cliff/Roadway2.htm

Minh Phan, T., Park, D.-W., & Ho Minh Le, T. (2021). Improvement on rheological property of asphalt binder using synthesized micro-encapsulation phase change material. *Construction and Building Materials*, *287*, Article 123021. https://doi.org/10.1016/j.conbuildmat.2021.123021

NSDI. (2022). *National Spatial Data Infrastructure Portal*. http://data.nsdi.go.kr/

Public Data Portal. (2022). *Public Data Portal*. https://Www.Data.Go.Kr/. https://www.data.go.kr/

Ramer, J. (1993). An empirical technique for diagnosing precipitation type from model output. *5th International Conference on Aviation Weather Systems,* Vienna*,* 227–230.

Souayfane, F., Fardoun, F., & Biwole, P.-H. (2016). Phase change materials (PCM) for cooling applications in buildings: A review. *Energy and Buildings*, *129*, 396–431. https://doi.org/10.1016/j.enbuild.2016.04.006

Szklarek, S., Górecka, A., & Wojtal-Frankiewicz, A. (2022). The effects of road salt on freshwater ecosystems and solutions for mitigating chloride pollution – A review. *Science of The Total Environment*, *805*, Article 150289. https://doi.org/10.1016/j.scitotenv.2021.150289

Toms, B. A., Basara, J. B., & Hong, Y. (2017). Usage of existing meteorological data networks for parameterized road ice formation modeling. *Journal of Applied Meteorology and Climatology*, *56*(7), 1959–1976. https://doi.org/10.1175/JAMC-D-16-0199.1

Wikipedia. (2022). *Geographic information system*. Wikipedia. https://en.wikipedia.org/wiki/Geographic_information_system

Zilioniene, D., & Laurinavicius, A. (2007). De-icing experience in Lithuania. *The Baltic Journal of Road and Bridge Engineering*, *2*(2), 73–79. https://bjrbe-journals.rtu.lv/article/view/1822-427X.2007.2.73%E2%80%9379/2252