Using Vehicular Sensors to Estimate Road Surface Temperature Variation: An Effective and Lower Cost Alternative to Embedded Sensors

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Abstract: This paper examines whether ubiquitous vehicular ambient temperature (VAT) sensors can effectively mimic the patterns of road surface temperature variation collected using a thermal mapping equipment. Our research analyzed the reliability of road surface temperature data collected from VAT sensors and a thermal mapping, and the similarity of the patterns of road surface and ambient temperatures. In addition, this research developed a way to segment roadway based on variation in road surface temperature. This segmentation is useful to road authorities. Although VAT sensors do not provide highly accurate temperature readings, they can identify patterns of surface road temperature on roadway sections. This information can be used so that individual drivers, commercial vehicle and fleet operators and road authorities acquire critical real-time information on road conditions. Further, using these sensors instead of fixed sensors or thermal mapping can significantly reduce road maintenance costs.

Keywords: Road Surface Temperature, Vehicle Sensor, Winter Maintenance, Road Safety, Road Maintenance

1. INTRODUCTION

When extreme weather arrives, road safety and travel times can be severely affected. Even heavy rain and dense fog can cause significant traffic congestion and delays. During cold weather, the patterns of road surface temperature variation are of great significance in terms of traffic safety and traffic operations. Measuring and forecasting road surface temperatures are an important task for road authorities. The negative impacts of using too little deicing material are accidents and road closures, but excessive use has negative impacts on the environment, road maintenance budgets and road surface lifetimes.

There are three primary ways to measure road surface temperatures. 1) Embed road surface temperature sensors in roadway sections, 2) Install non-contact infrared thermometers in roadway sections, and, 3) Using a thermal mapping that can capture patterns of road surface temperature variation by repeatedly driving on the same roadway sections at the same

time of day. The third option is attractive because it can provide valuable information on the temperature of whole roadways, while the first two options measure temperature only where sensors are installed. The cost of installing and maintaining sufficient sensors is very high. For example, the estimated cost of installing a single fixed sensor is over $125 thousand dollars. That includes the cost of the sensor and installation, but not long term maintenance, which can also be expensive. As of 2015, there were 20 embedded sensors on national highways and freeways in Korea and there is a plan to install an additional 20 in the near future. The estimated cost for these new sensors will be more than 2.5 million dollars.

Predicting road surface temperatures involves complicated procedures and requires a vast amount of input data. Weather conditions such as temperature, humidity, degree of insolation (incoming solar radiation) and cloud cover can be used to predict road surface temperature over 3, 6 or 12 hour periods based on various models. The predicted values can be compared to measured values to evaluate the reliability of the predicted patterns of variation. Most of the current prediction models are site-specific and must therefore be re-calibrated for each new site. Information on road surface conditions is important for road management authorities, commercial vehicle and fleet operators, navigation service providers, traffic information service providers and individual travelers. That information can reduce the risk of traffic accidents by informing the selections of routes when roadways are at high risk of freezing and/or sections are exposed to a high likelihood of black ice.

Patterns of road surface temperature variation are closely related to spatial characteristics of roadway sections such as topographical conditions and pavement characteristics. Road surface temperature may exhibit a fairly regular pattern of variation depending upon such spatial characteristics. The biggest factor in changing temperatures is weather. Variation intensity of surface road temperature changes based on current weather conditions. For example, maximum radiative heat loss incurs on road surfaces when there is light wind and clear skies. When the weather is humid and windy, radiative heat loss from road surface is at a minimum, causing little variation in surface temperatures.

Our research examines whether temperature readings collected from vehicular ambient temperature (VAT) sensors can accurately estimate patterns of road surface temperature variation and thus replace road surface temperature readings collected from a thermal mapping or fixed sensors. To do so, we examined patterns of road surface temperature variation collected under various weather conditions. We also examined the statistical significance of differences in road surface temperatures measured using a thermal mapping and those collected from VAT sensors on the same roadway sections and time periods. The research procedure is shown in are shown in Figure 1.

Set the Survey Plan
• Select test routes • Confirm survey dates • Classify weather conditions

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Collect Temperature Data
• Road surface temperature data using thermal mapping system • Road ambient temperature data using vehicular ambient sensors

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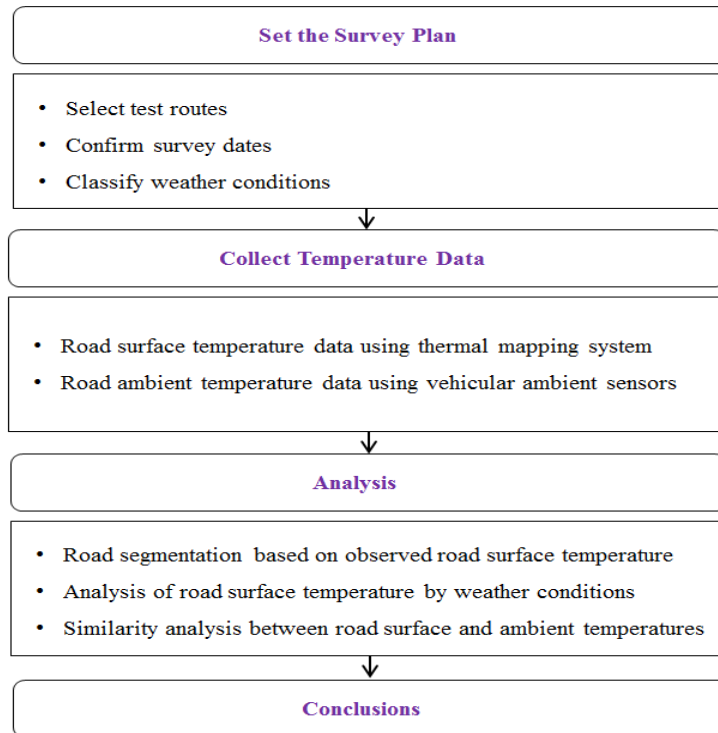| Analysis |
| --- |
| • Road segmentation based on observed road surface temperature
• Analysis of road surface temperature by weather conditions
• Similarity analysis between road surface and ambient temperatures |

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Conclusions

Figure 1 Research Procedure

2. LITERATURE REVIEW

Road authorities and highway officials require reliable road surface temperature information to make decisions for efficient treatment of major arterial highways during winter. Many researchers have been involved in projects to investigate the variation of road surface temperature on roadway sections vulnerable for freezing. In addition, many prediction models have been proposed to characterize temperature patterns. In order to improve the efficiency of road surface temperature prediction, verification of the spatial variation of road surface temperature along the route has to be ensured. However, even with rigorous design and installation of embedded sensors, the solutions are unable to reflect the real spatial variation of road surface temperature and surface state of the roads because covering all road surfaces with sensors is impossible. Regional road surface temperatures can vary as much as 10°C at any given time as a result of interacting meteorological and geographical parameters (Shao et al., 1996).

Thermal mapping, based on infrared thermometry allows for high resolution surveying of road surface temperatures. It has been used in applied road weather studies since the 1970s (Lindqvist, 1976). In the mid-1980s thermal mapping became a common practice in winter maintenance activities. Surveys are conducted using vehicle mounted infrared sensors under different weather conditions to generate datasets describing the spatial variation of road surface temperatures. These are called thermal fingerprints and can be used in numerical forecast models (Shao et al, 1997). Thermal fingerprints are associated with the exact location of each reading using GPS to overcome distance estimation errors that often occur during surveys (Chapman et. al., 2001). Chapman and Thrones (2005) proposed that such survey has to be conducted before sunrise in order to collect data that are representative of minimum temperatures. Also, Prusa et al. (2002) showed in their study that traffic loads are a major

source of potential error and therefore, measurements should take place before the dawn to measure the minimum surface temperature.

Forecasts of road surface conditions can be accomplished through different approaches. The most common model is the physical energy balance model where weather forecasts and measurements from road weather stations are used to predict road surface temperatures by applying energy balance equations (Sass and Lister, 1997; Korontenko, 2002; Takashi et al, 2006). These models show generally high accuracy but obstructions caused by hills, buildings and trees or other complex physical processes can reduce the accuracy of predictions (Kršmanc et al, 2013). In those cases the general models require further parameterizations required to overcome these complications (Shao and Lister, 1995). Other approaches are to apply neural network or other improvement techniques (Shao, 1998, Pasero and Moniaci, 2006), or to develop complex statistical models. Berrocal et al. (2010) suggested two statistical methods for forecasting the probability of ice formation while Sherif and Hassan (2004) examine relationship between road surface temperature and weather variables using statistical models.

A new approach based on principal components analysis (PCA) from thermal mapping data has been suggested to provide road surface temperature forecast of different weather situations and temperature ranges (Chapman et al, 2012). The proposed method shows interesting results explaining up to 80% of measurements. However, this approach relies on road surface temperature measurements which are not always available. Krismanc et al. (2013) applied partial least-square (PLS) regression in a study based on multivariate tools but these models must be developed for each specific location. Recently, Marchetti et al. (2015) proposed a methodology to forecast road surface temperature using both principal components analysis and partial least-square regression in an urban configuration and results shows excellent performance.

3. DATA DESCRIPTION

3.1 Data Acquisition

To explore road surface temperature, the test route was selected by considering different days and various weather and topographical conditions since they affect patterns of road surface and ambient temperature variation. Table 1 presents information about the test route.

Table 1 The Test Route Information

Route name	Distance	Characteristics
Jayuro JC ~ Songchoo IC Songchoo IC ~ Jayuro JC	50km (one-way 25km)	Tunnel (3.79km) Flat section (0~2% grade) Rural areas

The survey was conducted a total of 10 times along each route on a round-trip basis from 05:00 a.m. to 06:00 a.m. During the survey, a survey vehicle kept the same speed (80km/hr) and travelled in the same lane. Weather conditions on the survey days were based on weather forecast information provided by the Korea Meteorological Administration (KMA). Three types of weather conditions were established as shown in table 2, since patterns of road surface temperature variation are directly affected by current weather conditions. As a result, the patterns of road surface temperature variation under each weather condition can be examined.

Table 2 Weather Condition Classification

Weather Conditions	Description
A	Clear and wind-free
B	Slightly cloudy and windy
C	Cloudy/humid/windy

3.2 Thermal Mapping and Vehicular Temperature Sensors

A thermal mapping was employed to collect road surface temperatures on the test route. Figure 2 shows a survey vehicle equipped with thermal mapping system (see redboxes).

FIGURE 2 Thermal Mapping Systems

This consists of a power supply device, transmission equipment, an ambient temperature sensor, a humidity sensor, road surface temperature sensors (using non-contact infrared thermometers), GPS, a processor and various software applications for data processing. Figure 3 presents a diagram of the various sensors included in the thermal mapping system.
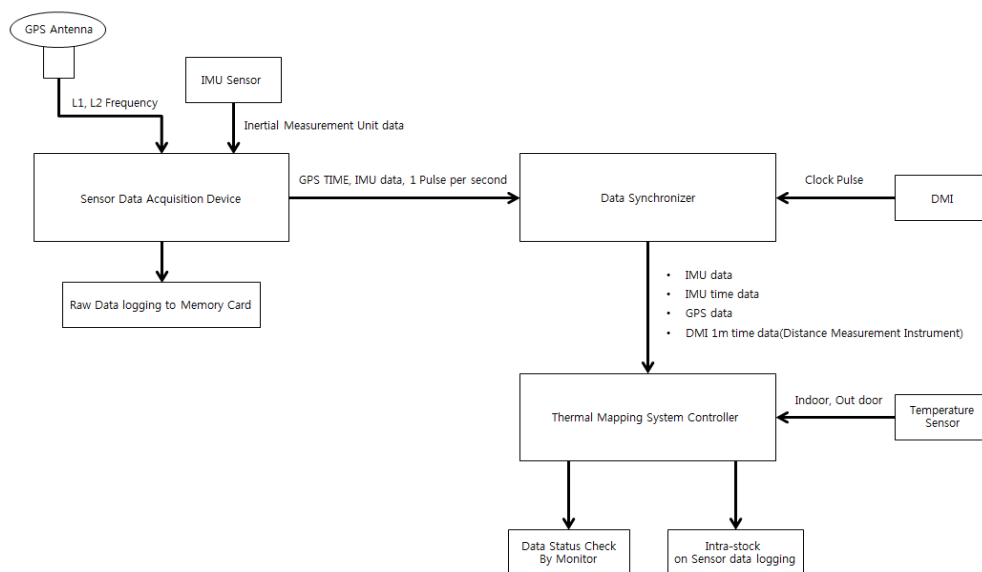

FIGURE 3 Diagrams for a Thermal Mapping System

Since the survey vehicle did not have VAT sensors, we attached them in both the front and rear of the vehicle. This enabled us to account for differing sensor locations based on passenger or commercial vehicle types. Before data collection on the test route, VAT sensors were tested in the lab to confirm that their readings were accurate.

4. STATISTICAL ANALYSIS

4.1 Summary of Correlation Analysis Results

Table 3 provides a summary of road surface and ambient temperature collected from thermal mapping and VAT sensors installed in a survey vehicle in the test route by direction. A total of 1,100 (Jayuro JC → Songchoo IC) and 1,650 (Songchoo IC → Jayuro JC) observations were collected.

Table 3 Summary of Road Surface Temperature Survey Results

Survey day	Road surface temperature (Jayuro JC→Songchoo IC)				
	Min.(℃)	Max.(℃)	Avg.(℃)	Standard deviation (℃)	Weather conditions
15.10.26	11.3	19.80	13.63	1.76	C
15.10.30	-0.1	13.69	4.28	3.15	B

Survey day	Road surface temperature (Songchoo IC→Jayuro JC)				
	Min.(℃)	Max.(℃)	Avg.(℃)	Standard deviation (℃)	Weather conditions
15.10.26	11.1	19.8	13.75	1.74	C
15.10.30	-0.1	13.7	6.43	2.72	B
15.11.03	3.1	13.9	5.34	1.98	B

Correlation analysis was performed in order to see if weather conditions classified using surveys were consistent with actual weather conditions. In other words, the main purpose is to verify whether road surface temperature variations collected on the same weather conditions, time period and roadway sections would be statistically significant. For this test, a Pearson correlation coefficient was used here as shown in equation 1 below.

$$\gamma = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y}$$

(1)

Where,

$\bar{x}$ = average road surface temperature x

$\bar{y}$ = average road surface temperature y

s_x = sample standard deviation of sample x

s_y = sample standard deviation of sample y

n = total number of road surface temperature data observations

When a Pearson correlation coefficient is above 0.3, then it indicates a correlation between two variables. Table 4 summarizes the person correlation coefficient.

Table 4 Summary of the Results (Songchoo IC → Jayuro JC)

Survey day	Weather conditions		Coefficient(γ)
15.10.26	C	Cloudy/humid/windy	-0.07
15.10.30	B	Slightly cloudy and windy	

Here, the correlation coefficient was relatively low and negative, so we can conclude that classified and actual weather conditions were not consistent. On the other hand, as indicated in table 5, road surface temperature in the opposite direction (Jayuro JC→Songchoo IC) shows a stronger positive correlation, but one that is still less than 0.3.

Table 5 Summary of the Results (Jayuro JC→Songchoo IC)

Survey day	26th , October of 2015	30th , October of 2015
Weather Conditions	C	B
Coefficient(γ)	-0.24	
Survey day	26th , October of 2015	3rd , November of 2015
Weather Conditions	C	A
Coefficient(γ)	-0.23	
Survey day	30th , October of 2015	3th, November of 2015
Weather Conditions	B	A
Coefficient(γ)	0.58	

As described in Table 5, correlation results indicated that Oct. 30th, 2015 and Nov. 3rd, 2015 is high (γ =0.58). Thus, the average of road surface temperatures on the two days was used to divide road sections as shown in table 6.

Table 6 Summary of Statistical Results

Survey day	Road surface temperature (Jayuro JC→Songchoo IC)				
	Min.(℃)	Max.(℃)	Avg.(℃)	Standard deviation (℃)	Weather conditions
15.10.26	11.3	19.8	13.632	1.76	C
15.10.30	-0.1	13.69	4.279	3.15	B

Survey day	Road surface temperature (Jayuro IC→Jayuro JC)				
	Min.(℃)	Max.(℃)	Avg.(℃)	Standard deviation (℃)	Weather conditions
15.10.26	11.1	19.8	13.75	1.74	C
Average 15.10.30 15.11.03	1.8	13.55	5.34	2.23	

Survey day	Ambient temperature (Jayuro JC→Songchoo IC)					
	VAT sensor	Min.(℃)	Max.(℃)	Avg.(℃)	Standard deviation(℃)	Weather conditions
15.10.26	Rear	10.1	18.3	12.98	1.89	C
	Front	12.2	19.2	14.95	1.57	C
Average 15.10.30 15.11.03	Rear	0.5	6.1	3.33	1.83	B
	Front	2.6	8	5.60	1.51	B

Survey day	Ambient temperature (Songchoo IC→Jayuro JC)					
	VAT Sensor	Min.(℃)	Max.(℃)	Avg.(℃)	Standard deviation(℃)	Weather conditions
15.10.26	Rear	9.9	15.9	13.77	1.43	C
	Front	12.9	22.5	15.62	1.36	C
Average 15.10.30 15.11.03	Rear	1.1	7.4	4.18	1.42	B
	Front	4.15	8.85	6.52	1.14	B

We can see that temperatures collected from VAT sensors attached on the front of the vehicle are always higher than those from the sensor attached on the rear of the vehicle. This is

presumably because readings are impacted by engine heat or heat released from the road surface during driving. Thus, data from the sensor attached on the rear of the vehicle should be employed to perform similarity analysis. According to the results, both thermal mapping and VAT sensors produce similar temperature data along with the test route associated with weather conditions. Therefore, VAT sensors are a valid alternative to the more expensive thermal mapping and the much more expensive fixed sensors.

4.2 Road Segmentation based on Surface Road Temperature

Our research then developed a sensible way to divide road sections from the perspective of consecutive variation in road surface temperature. Specifically, it segmented roads based on road surface temperatures collected from thermal mapping and compared these to the average value of road sections and associated road surface temperature data. Roadway sections for analysis are defined using this method as the number of sections in which individual temperature difference with average road surface temperature exceeds 1.0℃. For example, as shown in Figure 4, the average of each road section was 4.77℃ up to the 3rd data point but the difference between the average and the next immediate data, which is the 5th data point, was more than 1.0℃. In this case, the new average by section from the 6th data point should be calculated and compared with the next data, and Y, which is the new divided value, becomes the average temperature of road sections. Figure 4 represents a specific example of the suggested method.

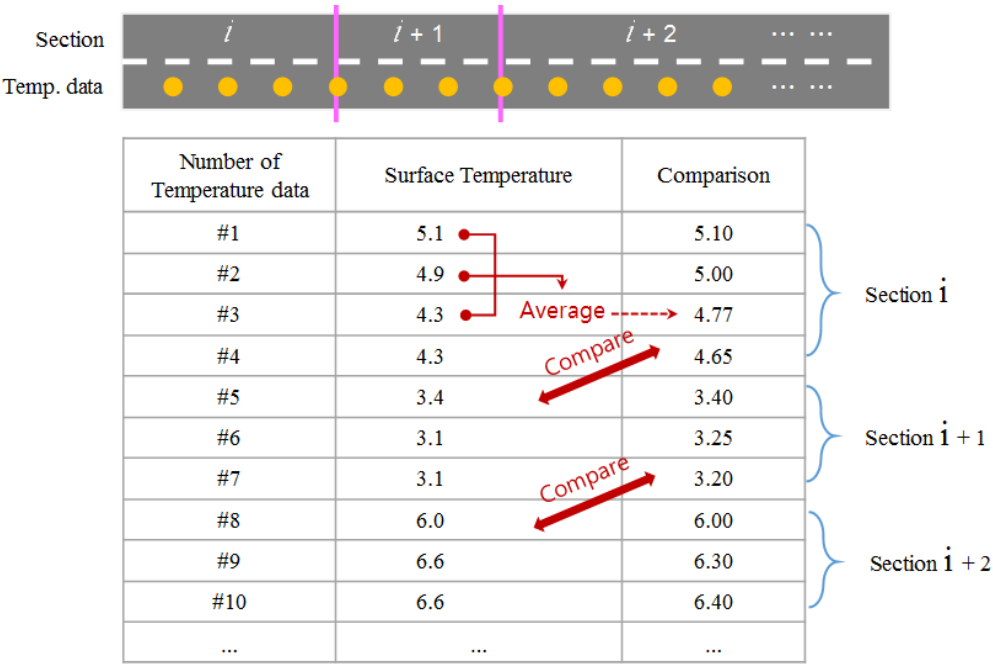| Number of Temperature data	Surface Temperature	Comparison	
#1	5.1	5.10	
#2	4.9	5.00	
#3	4.3	Average ----> 4.77	Section i
#4	4.3	4.65	
#5	3.4	3.40	
#6	3.1	3.25	Section $i+1$
#7	3.1	3.20	
#8	6.0	6.00	
#9	6.6	6.30	Section $i+2$
#10	6.6	6.40	
...	...	...	

FIGURE 4 Specific Road Segmentation Method

Road sections are divided based on final results of the road surface temperature survey over the test route and the results are shown in Table 7.

Table 7 Results of Road Segmentation

Survey day	Survey section	Total number of observations	Road section division (n)
15.10.26	Jayuro JC→Songchoo IC	1,100	25
15.10.30			70
15.10.26	Songchoo IC →Jayuro JC	1,650	52
Avg. 15.10.30 15.11.03		1,364	61

The statistical significance between road surface temperatures collected through a thermal mapping and VAT sensors was analyzed based on the four different roadway sections classified according to weather conditions.

4.3 Similarity Analysis between Road Surface and Ambient Temperature Readings

The analysis conducted a paired t-test to see if the difference between road surface and ambient temperature is statistically significant. A paired t-test is typically used to compare the average of two different groups of samples but it can also be conducted to analyze significance of differences on data collected with using different methods. Intuitively, we should observe differences in the patterns of temperature variations. Accordingly, the null hypothesis is that a temperature difference exists, while the alternative is that no difference is observed. Table 8 represents a summary of paired t-test results.

$H_0 : \bar{x} \neq \bar{y}$: Pattern of temperature variation is not the same

$H_1 : \bar{x} = \bar{y}$: Pattern of temperature variation is same

Table 8 Summary of Paired T-Test Results

Survey date	Direction of the test route	Total no. of data	Road section (n)	Front sensor versus surface temperature	Rear sensor versus surface temperature
15.10.26	Jayuro JC → Songchoo IC	1,100	25	P-value : 0.045	P-value : 0.0004
15.10.30			70	P-value : 0.038	P-value : 0.0001
15.10.26	Songchoo IC → Jayuro JC	1,650	52	P-value : 0.01	P-value : 0.0001
Average 15.10.30 15.11.03		1,364	61	P-value : 0.01	P-value : 0.002

The P-value in all paired t-tests was lower than 0.05, which is the level of significance selected for this test. Therefore, the alternative hypothesis that assumes that "pattern of two temperature variations is same" should be adopted (H_0 is correct when p-value is greater than 0.05, H_1 is correct when p-value is smaller than 0.05). This means the patterns of

temperature variation collected from VAT sensors are statistically comparable to patterns of road surface temperature variation collected from a thermal mapping. Please note that this is only true under dry conditions, if the road surface is wet then the intensity of variation of the road surface temperature is much higher.

5. CONCLUSIONS

This research was performed to analyze both the reliability of road surface temperatures collected from thermal mapping and the similarity between road surface temperature and ambient temperature on the same route and weather conditions using statistical techniques. Prior to discussing the validity of this research, we note that one critical fact should be examined. In general, it is known that vehicular ambient temperature sensors cannot precisely measure roadside temperature due to various environmental reasons. For example, abnormally high vehicular ambient temperature readings are presumed to be caused by environmental factors such as road surface heat. The US National Weather Service (US NWS) recommends temperature sensor to be installed 5 ~ 10ft (1.523 – 3.038m) away from heat released from the engine, asphalt and concrete, tires. Namely, the US NWS has developed its own standard for ambient temperature collection and it has been shown to be quite precise. It is logical that temperature from vehicular ambient temperature sensors should be interpreted as providing a valid temperature range, rather than a precise value. Although vehicular ambient temperature sensors do not provide highly accurate temperature estimates, it is possible to use them in order to identify patterns of surface road temperature overall road sections. Thus, this information can be used so that individual drivers, commercial vehicle operators, fleet managers and road agencies acquire effective information on road conditions at minimum cost during the winter. Theoretically, all vehicles that have vehicular ambient sensors that can collect road ambient temperatures because they have on-board diagnostics (OBD) systems which gives the vehicle owner or repair technician access to the status of the various vehicle subsystem. However, in reality, a patrol vehicle that belonging to road authorities or commercial vehicles can collect and provide data to a traffic management center. The proposed road segmentation method can be employed to establish specific sections vulnerable roadway sections for freezing during winter. Such information can be used to determine the best places to install fixed sensors. In summary, information gathered from VAT sensors has the potential to provide accurate information at low cost compared to installing more temperature sensors, road surface temperature sensors and thermal mapping systems.

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