Developing a Method to Predict Road Surface Temperatures -Applying Heat Balance Model Considering Traffic Volume-

Naoto Takahashi [1], Roberto A. Tokunaga [2], Motoki Asano [3] and Nobuyoshi Ishikawa [4]

[1] Civil Engineering Research Institute of Hokkaido
1-3-1-34, Toyohira-ku, Sapporo, 062-8602 Japan
Email: takahashi-n24k@ceri.go.jp
[2] Civil Engineering Research Institute of Hokkaido, Email: roberto-1097ga@ceri.go.jp
[3] Civil Engineering Research Institute of Hokkaido, Email: m-asano @ceri.go.jp
[4] Institute of Low Temperature Science, Hokkaido University, Email: nobu@pop.lowtem.hokudai.ac.jp

ABSTRACT

With wintertime comes the potential for icy, slippery roadways, which result in decreasing the level of traffic performance on roadways. Road authorities regularly take anti-icing and -slippery procedures to prevent snow or ice from bonding to road surface. However, as the amount of those uses tends to be increased from year to year, it requires more efficient snow and ice control with the proactive preventive approach being desirable to apply early enough to ice from forming. Thus, the more-efficient works needs developing an appropriate method to predict road surface icing conditions. Our research group works in developing a method for surface-icing forecast with applying a heat balance model, with the intention of providing "Strategic Snow and Ice Control" which takes the proactive winter maintenance strategy. This paper describes the research framework and attempts to demonstrate how the heat-balance model developed here works to predict road surface temperature.

Keywords: road surface temperature, heat balance model, strategic snow and ice control

1. INTRODUCTION

The City of Sapporo, the prefectural capital of Hokkaido, is the Japan's fifth largest city with a population of approximately 1.85 million in 2005. The City is one of the few metropolitan cities with severe, snow-covered winter in the world; indeed, the City has the annual cumulative snowfall reaching five meters (Fig. 1.), and the city's average temperature from December to February goes below 0 degree Celsius (Fig. 2.).

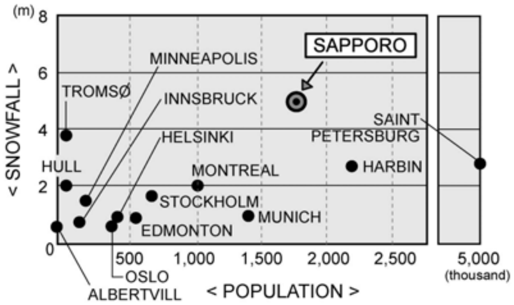
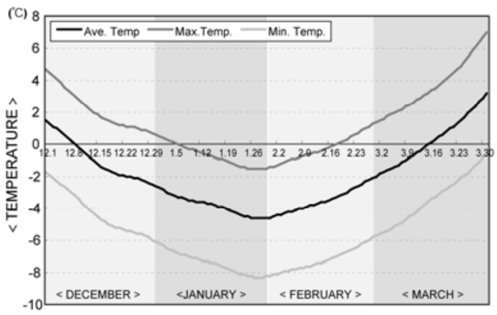


Fig. 1. Comparing snowfall & population among world northern metropolis



	AVERAGE YEAR TEMPERATURE		
	AVE.	MAX.	MIN.
Dec.	-1.0	2.1	-4.4
Jan.	-4.1	-0.9	-7.7
Feb.	-3.5	-0.3	-7.2
Mar.	0.1	3.5	-3.5

Fig. 2. Sapporo's temperature variation (Dec.1, 2004 ~ Mar. 31, 2005)

In Sapporo, not only residents' daily activities but also business and industrial activities depend heavily on automobile mobility. Road conditions in winter, nevertheless, have get worse because of heavy snowfall and freezing temperatures; otherwise, the level of traffic performance is deteriorated by snow-and ice-covered road surface. This surface condition leads to delays in vehicle movement and speed, and requires longer distances to slow down than in dry conditions: these could cause traffic-congestion and accident.

Road authorities attempt to provide as good roadway condition as possible through various snow and ice control activities. Especially, the practice of anti-icing and spreading abrasives is recognized as the primary winter maintenance strategy. However, the amount of anti-icing chemicals tends to be increased (Fig. 3.).

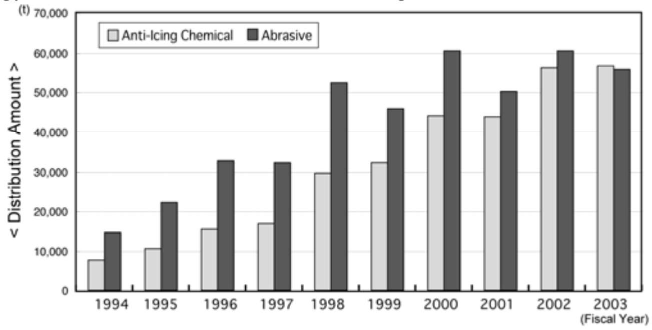


Fig. 3 Amount of anti-icing and abrasive use on Hokkaido's national highways

Anti-icing is a proactive preventive strategy being desirable to apply chemical applications early enough to ice from forming (Hokkaido Development Bureau, 1997). This practice requires forecasting accurately road-surface conditions for winter maintenance decision. However, the Sapporo's highest temperature only reaches -2 degree Celsius during the coldest period of the year (Mid-January) with the daily cycle of icing formation and melt (Fig. 4.). This is the critical problem leading to the potential for winter-typed traffic accidents. Indeed, many winter traffic accidents mainly caused at the temperature range between -6 and 0 degree Celsius (Fig. 5.). Therefore, in order to strategically provide anti-icing operation at the right times and places, it is especially important to forecast wintertime road-surface conditions, whether icy or not, based on the prediction of road-surface temperature, which is the single most important determinant for road condition.

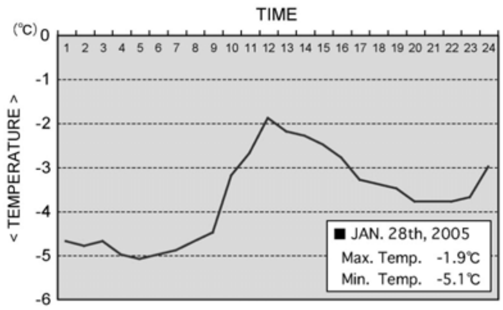


Fig. 4. Daily temperature variations during the coldest period

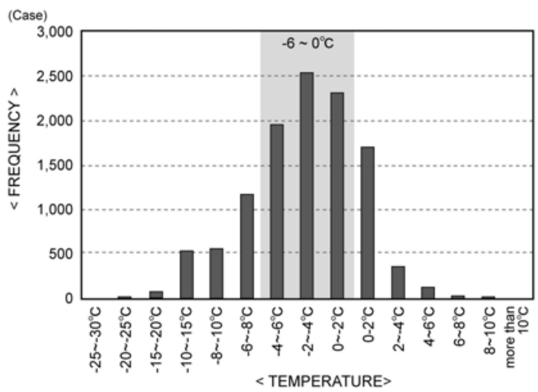


Fig. 5. Frequency of winter accident caused by slippery roads by temperature

2. STUDY METHODS

The research plan is to first determine an appropriate method to predict road-surface temperatures through an extensive review of available literature that provides insights into road-surface temperature modeling. Then, comparing two major approaches, "Statistical Modeling" and "Heat-Balance Modeling," we employ the heat-balance with its extensive advantages and popularity within the road weather community. The second step is to identify the basic prediction model that calculates the heat gains and losses at the pavement surface. Using the heat-balance model developed in the previous step, the third phase is to collect all relevant data through subsurface temperature measurement (primary source) and weather observation (secondary source). Finally, we calculate the predicted road-surface temperatures with the collected data and evaluate its model performance.

3. SELECTING A METHOD TO PREDICT ROAD SURFACE TEMPERATURE

There are two basic approaches to predict road surface temperature. One is a statistical modeling technique: the other is a heat-balance modeling technique (Kondo, 1994. Fukuhara et al., 2005.). Table. 1. describes the characteristic of each modeling.

Table 1. Comparing statistical modeling and heat-balance modeling

	Statistical Modeling	Heat-Balance Modeling
Summary	Predict road surface temperature by multiple linear regression analysis with applying the weather data from meteorological observatory or roadway weather monitoring "Telemeter" system.	Predict road surface temperature by subtracting the heat applied to the road surface from the heat radiating from the road surface, which shows the process of energy balance.
Advantage	Relatively easier method to predict.	Being able to apply any sites to predict if collecting the energy balance data.
Dis-advantage	Being unable to apply the linear multiple regression equation being established for the specific location into other locations; otherwise, needing to collect and analyze data for each location.	Being little more complicated prediction method as requiring to calculate every energy balance.

There is no simple way of judging the performance between the models, as there has not been any comprehensive scientific review of the models utilized by the road weather community. However, as Mahoney and Wagoner (2005) report, the majority of the models used operationally are heat balance models that predict the temperature profile from the pavement surface down several feet into the subsurface layer. Indeed, the heat-balance approach is now increasingly utilized in the U.S. and Europe, with either supplanting or complementing other approaches. For instance, in the U.S., the Wisconsin Department of Transportation (2005) has proposed that the road and bridge temperature prediction should be based on a thermal energy balance and/or empirically based model. Another example is in Sweden which combines energy balance with statistical model to calculate road surface temperatures for the coming 1 to 4 hours (Gustravsson, 1997).

One of the main reasons for using the heat-balance approach is that it can apply at large scale once developed the model: otherwise, it does not need to develop the equations to calculate road-surface temperatures site by site, like the statistical modeling approach. Another reason is that it requires the relatively short forecast time, which is useful in guiding road authorities for winter maintenance decision. Besides, the statistical approach is not reasonably applicable to predict road-surface temperatures in urban road setting, which is very complicated, as varying block by block. Therefore, with its wide application and operational advantage, we take heat-balance modeling for this study.

4. DEVELOPING THE BASIC TEMPERATURE PREDICTION MODEL

The research on road-surface temperature variation by Miyamoto and Asano (2002) has recognized that road-surface temperatures vary significantly depending on not only atmospheric condition such as sunshine but also roadway structures such as paved roadways or bridges. Besides, another considerably factor influencing road-surface temperatures is thermal energy released from running vehicles (Ishikawa et al., 2000. Prusa, 2002).

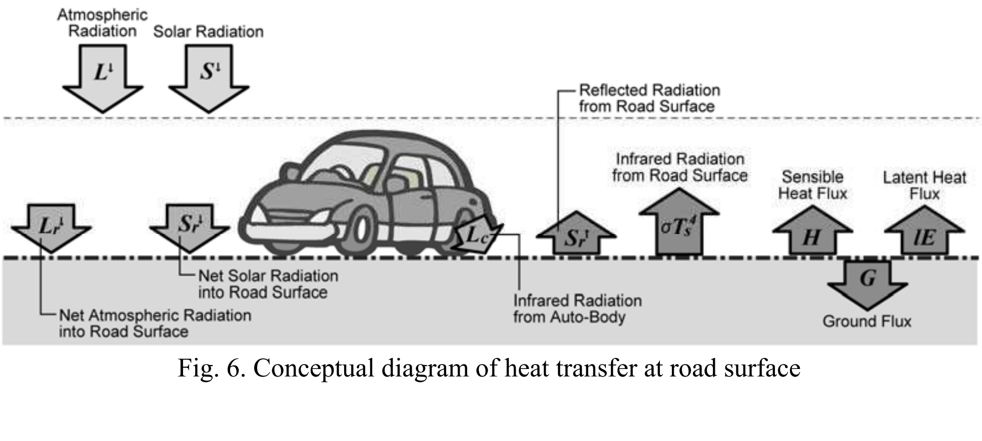


Fig. 6. Conceptual diagram of heat transfer at road surface

Fig. 6. shows a conceptual diagram to model the transfer of heat through road surface. The vehicle-related factors influencing road-surface temperatures include net atmospheric and solar radiations, which are screened by vehicles, into road surface and infrared radiation from auto-bodies: these factors are varied by traffic volume. One hand, the energy inputted into road surface after receiving vehicles' effects is distributed as infrared radiation, sensitive heat, latent heat, and ground flux from road surface. Then, road-surface temperature can be determined as a result of this heat transfer through the surface. This is a major component of the heat-balance, and on paved roadways it is shown in the following equation (1) or (2).

$$R^{\downarrow} = \sigma T_s^{\ 4} + H + lE + G \qquad (1),$$

where σ is the Stephan-Portman coefficient (=5.67×10^{-8}W $m^{-2}K^{-4}$), T_s is the road-surface temperature (K), H is the sensible heat flux (W/m^2), lE is the latent heat flux (W/m^2), G is the ground flux (W/m^2), and $R^{\downarrow}$ is the energy inputted to road surface (W/m^2).

$$R^{\downarrow} = S_r^{\ \downarrow} - S_r^{\ \uparrow} + L_r^{\ \downarrow} + L_c \qquad (2),$$

where $S_r^{\downarrow}$ is the net solar radiation into road surface (W/m^2), $S_r^{\uparrow}$ is the amount of reflected radiation from road surface (W/m^2), $L_r^{\downarrow}$ is the net atmospheric radiation into road surface (W/m^2), and L_c is the amount of infrared radiation from auto-bodies (W/m^2).

The parameters applied into equation (1) are presented in the equations from (3) to (5). Symbolizing H as the sensible heat flux and lE as the latent heat flux, the study shows these parameters with resulting from use of bulk method.

$$H = C_p \rho C_h U (T_s - T_a) \qquad (3),$$

$$lE = \rho \frac{0.622l}{P} C_e U (e_s - e_a) \qquad (4),$$

where C_p is the specific heat in air (1005Jkg^{-1}K^{-1}), ρ is the density of humidity (1.29 kgm^{-3}), C_h is the coefficient showing the magnitude of turbulent diffusivity by conveying the sensible heat (bulk coefficient), C_e is the coefficient showing the magnitude of turbulent diffusivity by conveying the latent heat (bulk coefficient), T_s is the road-surface temperature (K), T_a is the air-temperature (K), U is the wind speed (m/s), l is the latent heat of vaporization (2.5×10^6Jkg^{-1}), P is the atmospheric pressure (hPa), e_s is the vapor pressure on road surface (hPa), and e_a is the vapor pressure in atmosphere (hPa).

As supposing that the bulk coefficient for the sensible heat and latent heat has the same value, the study defines them as 0.003 (see Table. 2.). The atmospheric pressure used in this study is fixed as 1000 hPa, and the relative humidity on road surface is defined as 0.5 as if it were a dried road surface (see Table. 2.).

Symbolizing G as the ground flux, it is given as:

$$G = \kappa \frac{T_s - T_g}{\Delta z} \qquad (5),$$

where κ is the heat conductivity (Wm^{-1}K^{-1}), and T_g (K) is the subsurface temperature at depth of Δz (m) under the roadway. Here, supposing that the targeted road surface for this study might be the asphalt pavement, the heat conductivity is defined as 0.7 (Wm^{-1}K^{-1}), and the road-surface temperature used for calculating the ground heat flux applies the value of 50 mm depth.

From equation (6) to equation (11) describes the parameters applied into equation (2). equation (2) can be presented with employing the Albedo method (α = Reflectivity), and it is given by the following:

$$R^{\downarrow} = S_r^{\ \downarrow} - S_r^{\ \uparrow} + L_r^{\ \downarrow} + L_c = (1-\alpha) S_r^{\ \downarrow} + L_r^{\ \downarrow} + L_c \qquad (6)$$

$S_r^{\downarrow}$ is the net solar radiation into the road surface (W/m^2), and it is founded by using equation (7):

$$S_r^{\ \downarrow} = t_r \cdot S_s + (1 - t_r) S^{\downarrow} \qquad (7),$$

where t_r is the time vehicles passing through the study point, S_s is the strength of the scattered-radiation (W/m^2), and $S^{\downarrow}$ is the net solar radiation during clear days (W/m^2). Then, the time vehicles passing through the point *(t_r)* is determined by the following equation (8):

$$t_r = \frac{l \cdot N}{1000v} \qquad (8),$$

where l is the average length of vehicles (m), N is the traffic volume (vehicle/h), and v is the average speed of vehicles (km/h).

The net atmospheric radiation into the road surface ($L_r^{\downarrow}$) is given in the following equation (9), with taking into account the pavement screened by running vehicles:

$$L_r^{\ \downarrow} = (1 - t_r) L^{\downarrow} \qquad (9),$$

$L^{\downarrow}$ is the atmospheric radiation when the pavement is not screened by running vehicles, and this is founded by using equation (10):

$$L^{\downarrow} = \sigma T_a^{\ 4}\left[1-\left(1-\frac{L_f^{\ \downarrow}}{\sigma T_a^{\ 4}}\right)C\right] \qquad (10),$$

where T_a is the air temperature (K), $L_f^{\downarrow}$ is the net atmospheric radiation during clear days (W/m^2), C is the amount of clouds, n is the cloud amount in all sky layers, n_L is the amount of clouds in lower sky layers, and e_a is the vapor pressure in the atmosphere (hPa). Here, the could amount (C) is determined by:

$C = 1-(0.095-0.0006e_a)n-(0.66-0.0044e_a)n_L$ during overcast weather conditions, and

$C = 1-(0.85-0.007e_a)n$ when raining conditions.

The infrared radiation from automobiles (L_c) is founded by using equation (11):

$$L_c = \varepsilon\sigma T_v^{\ 4} \qquad (11),$$

where ε is the emissivity of the outgoing long-wave radiation from auto-body (≈1.0), σ is the Stephan-Portman coefficient (=5.67×10^{-8}W/m^{2}K^4), and T_v is the temperature at the bottom part of auto-body (K).

By using equation (3) to equation (5), equation (1) can be rewritten as follows (12). Then, equation (2) can be represented in equation (13) by using equation (6) to equation (11):

$$R^{\downarrow} = \sigma T_s^{\ 4} + C_p\rho C_h U(T_s-T_a)+\rho\frac{0.622l}{P}C_eU(e_s-e_a)+\kappa\frac{T_s-T_g}{\Delta z} \qquad (12),$$

$$R^{\downarrow} = (1-\alpha)\left[\frac{l\cdot N}{1000v}\cdot S_s+\left(1-\frac{l\cdot N}{1000v}\right)S^{\downarrow}\right]+\left(1-\frac{l\cdot N}{1000v}\right)\sigma T_a^{\ 4}\left[1-\left(1-\frac{L_f^{\ \downarrow}}{\sigma T_a^{\ 4}}\right)C\right]+\left(\frac{l\cdot N}{1000v}\right)\varepsilon\sigma T_v^{\ 4} \qquad (13),$$

Table. 2. shows the parameters necessary to calculate equation (12) and (13).

Table. 2. Parameter needed for heat-balance model calculation

Heat Balance Comp.	Parameter	Unit	Value
Radiation Amount $R^{\downarrow}$	Ave. Length of Vehicles l	m	5
	Ave. Speed of Vehicles v	km/h	Intersection: 5 Non-Intersection: 30
	Strength of Scattered-Radiating Light S_s	W/m^2	$S_s = 0.1S^{\downarrow}$ ($S^{\downarrow}$ shows all incoming light)
	Temp. of Vehicle T_v	℃	$T_v = T_a + 20$ (T_a shows temp.)
	Albedo α	−	0.1
Sensible Heat Flux H	Bulk Coefficient C_h	−	0.003
Latent Heat Flux lE	Bulk Coefficient C_e	−	0.003
	Relative Humanity rh_r	−	0.5
	Atmospheric Pressure P	hPa	1000
Ground Flux G	Heat Conductivity k	W/mK	2.1
	Depth Δz	m	0.05

This model is attempted to predict road-surface temperatures by resolving the complex heat-balance equations at road surface. Then, road-surface temperature can be determined by solving these equations with applying the Newton-Rhapson method.

5. ACQUIRING THE DATA

5.1 Applying Weather Data and Measuring Road Surface Temperature

The selected roadway for this study is the national highway Route 5, which is the typical urban arterial roadway running through the western part of the City of Sapporo (see Fig. 7.). Considering the temperature differences not only in sunlight availability, whether pavement being in sunshine or in shady, but also in roadway configuration (non-intersection or intersection), the study selects four observation points.

The primary data should be collected to calculate the heat-balance at the road surface include the subsurface temperatures, air temperatures, and wind speeds. The subsurface temperatures were measured at 8 different depths, from approximately 5mm to 300mm below the road surface. Taking into account the hindrance of snow removal operation, the thermometer was installed at the height of 2.5 m, and the anemometer was placed at the height of 3.0 m. All the primary data were recorded into the data loggers. Fig. 7. shows the outline of the measuring devices used in this study.

In addition to the primary data, the study employs the secondary data from the Sapporo District Meteorological Observatory, where is located at the distance of about 5 km from the study point. Those data include the amount of whole-sky sunlight, relative humidity (vapor pressure), and the cloud amount.

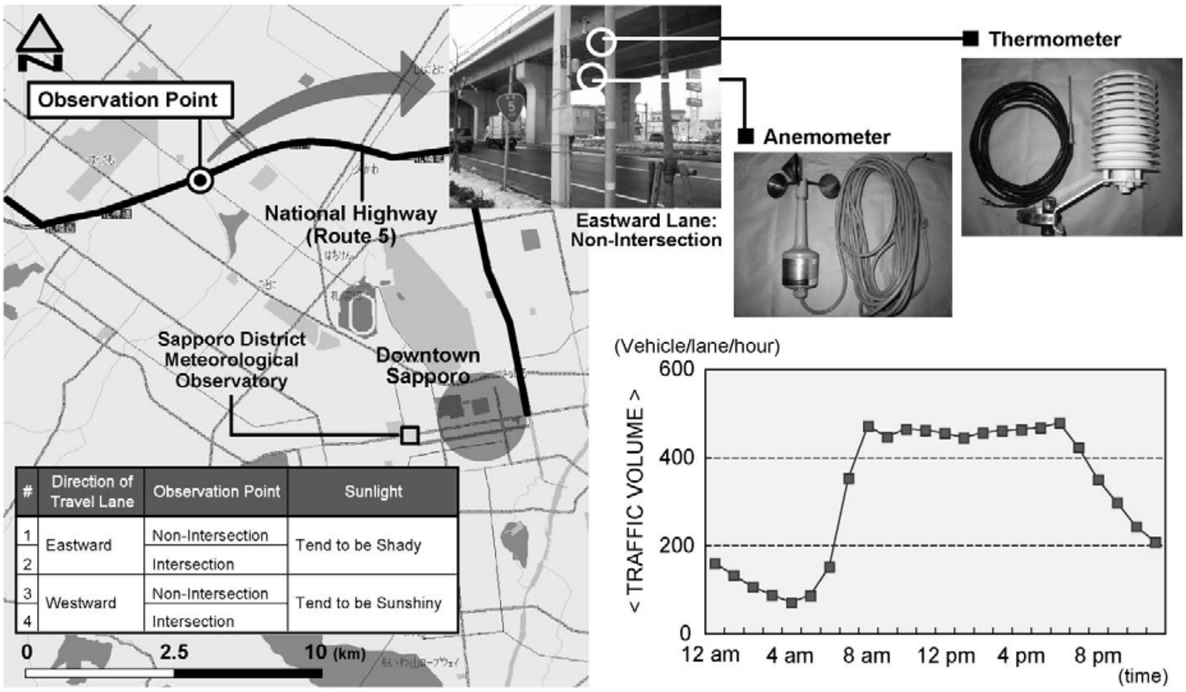


Fig. 7 Summary of observation point & observing elements and instruments

5.2 Traffic Volume

In addition to the weather-related information, the model is attempted to predict road-surface temperatures with considering traffic volume as a highly significant factor. Hourly traffic volume in this study was determined by directly counting the number of vehicles passing through the study area. As the traffic volume changes by the day, the surveys were conducted for eight days including the holiday and weekend. Then, the study determined a mean found from the survey result as the hourly traffic volume (Fig. 7.)

6. FINDINGS

As applying both the weather-related and traffic volume data to the heat-balance model, the study calculates the predicted road-surface temperatures. The calculation was made at the following days as intended for the days when the traffic-volume study was conducted.

A) From 7pm on January 18th to 11am on 19th
B) From 7pm on January 28th to 11am on 29th
C) From 7pm on February 9th to 11am on 10th
D) From 7pm to 11pm on February 28th

Fig. 8. shows the predicted road-surface temperatures calculated by using the heat-balance model and the directly measured road-surface temperatures (subsurface temperature of 5mm in depth) for the time periods of A) and B), and Fig. 9. shows the correlation of predicted versus measured values for all survey days. Besides, in order to evaluate the model performance, the study determines the Root-Mean-Square Error (RMSE), which indicates the average difference between the predicted and measured road-surface temperatures.

As shown in Fig. 8. and Fig. 9., the predicted values determined by using the heat-balance tend to be generally lower than the measured values, and it is clear that changes in temperature show a roughly similar tendency between the model-predicted and measured values. The RMSE shows the error of approximately 2 degree Celsius, but as shown in Fig. 8, during the nighttimes tend to be larger differences. There are a number of expectable factors leading to this difference. For instance, traffic volume might be one of them, but it might have a little effect on the model's performance due to little traffic volume during the nighttime (see Fig. 7.). Therefore, we consider the effect of traffic volume might be small. The other expectable factor is the underestimating of the energy inputted to the road surface from surrounding high-rise buildings, and it might be one having a more significant effect on this difference. Indeed, Narita (2001) points out that downward long-wave flux from surrounding buildings and structures should be involved in the net atmospheric radiation. However, the study has not considered the downward long-wave radiation from buildings along the roadway and the elevated highway running parallel to the roadway, which might result in underestimating the net atmospheric radiation into the road surface ($L_r^{\downarrow}$).

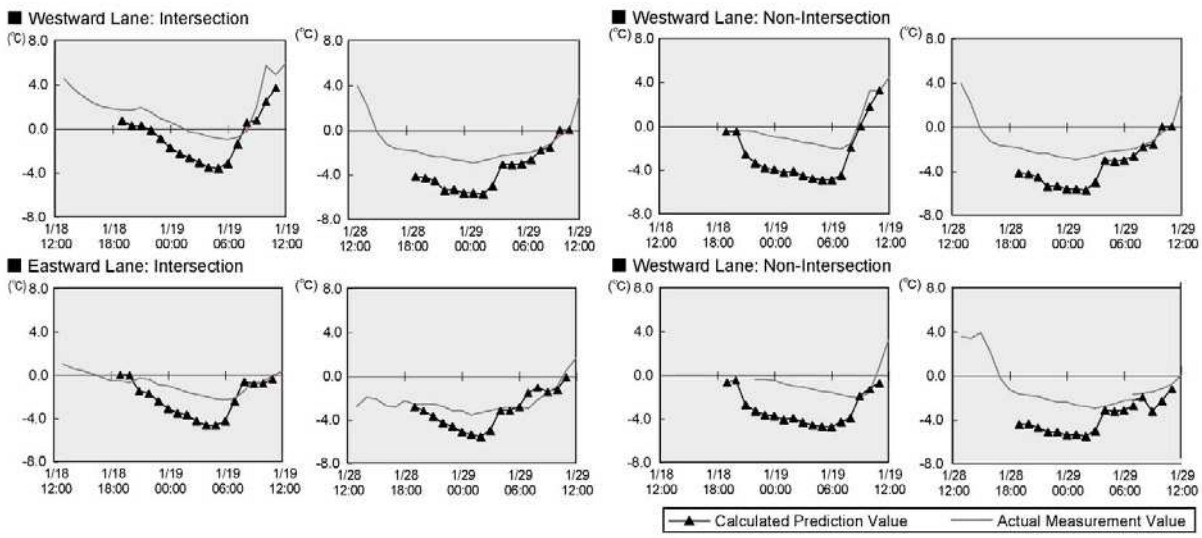
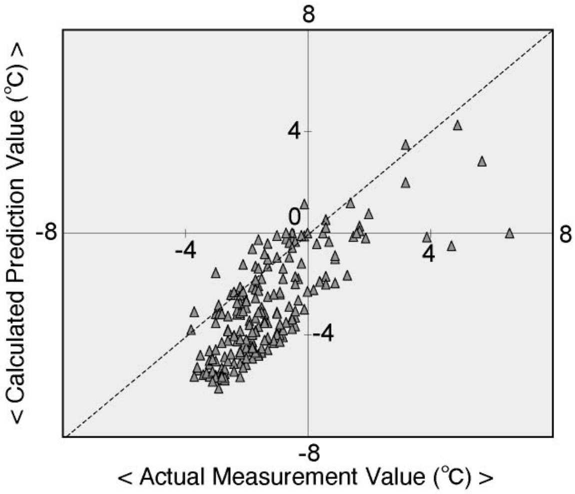


Fig. 8. Predicted values and measured values (5 mm in depth)



$$RMSE = \sqrt{1/n \sum_{i=1}^{n} (y_i - \hat{y}_i)^2}$$

y_i = Calculated Predication Value
$\hat{y}_i$ = Actual Measurement Value

Fig. 9. Predicted values versus measured values

7. CONCLUSIONS AND FUTURE STUDY

Throughout the course of this paper, we have attempted to demonstrate how the heat-balance model works for road-surface temperature prediction, which enhance providing “Strategic Snow and Ice Control Operation” by improving the road-surface icing condition forecast. The study explores the reliability of the heat-balance model with comparing the predicted road-surface temperatures with the measured values, and it shows the relatively smaller value of Root Mean-Square Error (RMSE). Consequently, even if the follow-up studies with more data are required to support our experimental findings, the model can be thought of as explanation for the potential rewards of road-surface temperature prediction in which the model could practically predict road-surface temperature variations, especially during daytimes.

Based on the study result, the following suggestions for future research are made:

- *Develop a Heat Balance Model by Every Type of Roadway Structure:* This study has developed the basic-typed heat-balance model for paved roadways. However, as bridges have different temperature features from paved roadways, it needs developing a model considering such as roadway structure.

- *Improve Model Performance:* The problem on the prediction during nighttime is still remained, as during the nighttimes demonstrates poor model performance. This is the next-study's main theme that improves the performance by identifying and valuing the factors of the differences between the predicted and measured values. Especially, not considering the downward long-wave radiation from surrounding buildings might lead to give a great influence on its negative result during nighttime where there is no daylight. We have planned to measure the actual amount of the long-wave radiation might be strongly related to energy balance at road surface in this winter.
- *Develop a Research Considering Roadway as "Path" rather than "Point":* This study predicts road-surface temperatures at every experimental "Point." However, as considering the practical use for road management, it is necessary to develop a research method considering roadway as "Path (Line)" rather than "Point." One possible approach is to recognize road-surface temperature distribution of a route by combining a result estimated by the model and a tendency of road-surface temperature distribution identified by using Thermal-Mapping method.
- *Develop the Forecast System Working with Weather Forecast:* It is essential to work with weather forecast for immediate road-surface temperature prediction at least. As considering the prediction reliability, it needs considering the details of data should be analyzed, as well as employing the data form the Automated Meteorological Data Acquisition System and the roadway weather monitoring "Telemeter" system.

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