This paper aims at examining the thermal influence of vehicle related heats (vehicle heats) on the road surface temperature and evaluating the validity of a vehicle road freezing forecasting (VRFF) model proposed by the present authors. Vehicle heats consist of the tire frictional heat, the vehicle radiant heat emitted downward from the bottom of a vehicle and the vehicle sensible heat due to vehicle-induced wind. In order to calculate the road surface temperature in a vehicle-passage area, the three vehicle heat fluxes are included in a heat balance equation of the road surface layer in addition to metrological heat fluxes.

A thermography observation targeted a roadway near a traffic light in Fukui city that has two-three lanes each way. Stopping and starting of vehicles (vehicles stop and go) are repeated due to the traffic light on only one side all day. It was shown that the difference in the road surface temperature on the lane between with and without the vehicles stop and go became clear as an atmospheric temperature fell. For example, the former was about 3.5°C higher than the latter in the nighttime. This is caused by the tire frictional heat and the vehicle radiant heat.

The validity of the VRFF model was identified by comparing the calculated road surface temperature with the experimental one obtained from the thermography observation. The VRFF model could reproduce almost the same temperature rise due to the vehicle heats as the outcome of the thermography observation.
INTRODUCTION

A technical tool, which can predict snow and ice (S/I) conditions on a road, is necessary to reconcile saving of road management cost as well as safe traffic in winter. There are many road freezing forecasting (RFF) models\(^{(1)-(3)}\), but most of them have not given careful consideration to thermal influence of vehicles on the S/I conditions. We, therefore, developed a vehicle RFF (VRFF) model\(^{(4)}\) including three kinds of vehicle related heats (vehicle heats), i.e. tire frictional heat, vehicle radiant heat emitted downward from the bottom of a vehicle and sensible heat due to vehicle-induced wind.

There has been, however, little field research on the influence of the vehicle heats on the road surface temperature. Consequently, the importance of the vehicle heats has not been fully discussed yet and the VRFF model has not attracted much attention till now.

This paper aims at examining the rise in the road surface temperature associated with the vehicle heats under stopping and starting of vehicles due to a traffic light (vehicles stop and go) through a field observation and evaluating the validity of the VRFF model.

HEAT TRANSFER THEORY FOR A DRY ROAD SURFACE

HEAT BALANCE EQUATION

Figure 1 shows the heat balance of a thin road surface layer subjected to the vehicle heat fluxes. The time variation of the road surface temperature, \( T_{ps} \) (representative temperature of the road surface layer with a thickness of \( \Delta z_s = 5 \text{ mm} \)), is calculated by Eq. (1):

\[
(\rho c)_p \frac{\partial T_{ps}}{\partial t} \Delta z_s = G + R_n + S_a + L + Q_v
\]

where \((\rho c)_p\) is the volumetric heat capacity of the road surface layer (J/m\(^3\)/K), \( t \) is time (s), \( G \) is the conductive heat flux across the bottom of the road surface layer (pavement heat flux, W/m\(^2\)), \( R_n \) is the net radiation flux (W/m\(^2\)), \( S_a \) is the sensible heat flux associated with natural wind (W/m\(^2\)), \( L \) is the latent heat flux associated with evaporation or condensation (W/m\(^2\)) and \( Q_v \) is the total vehicle heat flux (W/m\(^2\)). \( Q_v \) may consist of the tire frictional heat flux, \( S_t \) (W/m\(^2\)), the vehicle radiant heat flux emitted downward from the bottom of a vehicle, \( R_v \) (W/m\(^2\)), and the vehicle sensible heat flux due to vehicle-induced wind, \( S_{va} \) (W/m\(^2\)). Of course, \( Q_v \) is excluded from Eq. (1) outside a vehicle-passage area (for a non vehicle-passage area).

Under the road surface layer, the time variation of road temperature, \( T_p \) (°C), depends on the conductive heat flux.
Heat flux components across road surface

Pavement heat flux

Pavement heat flux, $G$, is given by Fourier’s law,

$$G = -\lambda_z \frac{\partial T_p}{\partial z} \bigg|_{z=0} \quad (2)$$

where $\lambda_z$ are the thermal conductivity (W/m/K) of the pavement in the vertical ($z$) direction.

Net radiation flux

Net radiation flux, $R_n$, is the sum of the net long-wave radiation flux, $R_{nl} (= R_{ld} - R_{lu})$, and the net short-wave radiation flux, $R_{ns} (= R_{sd} - R_{su})$, as shown in Figure 1. In which, $R_{lu}$ is the upward long-wave radiation flux from the road surface, $R_{ld}$ is the downward long-wave radiation flux from the sky, $R_{sd}$ is the incoming short-wave radiation flux and $R_{su}$ is the portion reflected upward. Thus,

$$R_n = R_{nl} + R_{ns} = R_{ld} - R_{lu} + R_{sd} - R_{su} \quad (3)$$

where $R_{lu}$ is calculated according to the Stefan-Boltzmann law,

$$R_{lu} = \varepsilon_p \sigma (T_{ps} + 273.15)^4 \quad (4)$$

where $\varepsilon_p$ is the emissivity of the road surface (0.95) and $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/m²/K⁴).

Sensible heat flux associated with natural wind

Sensible heat flux associated with natural wind, $S_a$, is evaluated using Newton’s law of cooling,

$$S_a = \alpha_s (T_a - T_{ps}) \quad (5)$$
where $\alpha_s$ is the heat transfer coefficient (W/m²/K) between the road surface and atmosphere and $T_a$ is atmospheric temperature (°C). The value of $\alpha_s$ is estimated from the natural wind velocity, $V_{ws}$ (m/s), using the following equation (5):

$$\alpha_s = 10.4V_{ws}^{0.7} + 2.2 \quad (6)$$

**Latent heat flux**

Latent heat flux on the road surface, $L$, is expressed as the product of the evaporative or the condensate mass flux, $m_v$, and the latent heat of vaporization, $h_v$. The value of $m_v$ may be proportional to the difference in vapor density between atmosphere and road surface. Consequently $L$ is calculated by the following equation,

$$L = h_v m_v = h_v \alpha_m (\rho_{va} - \rho_{vs}) \quad (7)$$

where $\alpha_m$ is the vapor transfer coefficient (m/s) and $\rho_v$ is the density of water vapor (kg/m³). Subscripts $s$ and $a$ refer to road surface and air, respectively. $\alpha_m$ is calculated in terms of $V_{ws}$ (6),

$$\alpha_m = 1.2 \times 10^{-2} V_{ws}^{0.6} + 0.4 \times 10^{-2} \quad (8)$$

**Vehicle related heat fluxes**

Total vehicle heat flux, $Q_v$, is given by the sum of the tire frictional heat flux, $S_t$, the vehicle radiant heat flux, $R_v$, and the vehicle sensible heat flux, $S_{va}$.

$$Q_v = S_t + R_v + S_{va} \quad (9)$$

$S_t$ may be calculated by Newton’s law of cooling,

$$S_t = \alpha_{tp} (T_t - T_{ps}) \quad (10)$$

where $\alpha_{tp} (= 60\text{W/m}^2/\text{K})(7)$ is the heat transfer coefficient between tire and road surface and $T_t$ is tire temperature (°C). $T_t$ is given by the following empirical correlation, regardless of road surface conditions (see Figure 2).

$$T_t = 0.9T_a + 0.33V_v \quad (11)$$

where $V_v$ is vehicle speed (km/h).

$R_v$ may be evaluated by the Stefan-Boltzmann law as a function of the temperature, $T_v$, on the bottom surface of the vehicle. That is

$$R_v = \varepsilon_v \sigma (T_v + 273.15)^4 \quad (12)$$
where $\varepsilon_v$ is the emissivity of steel ($= 0.80$).

The spatial variation of $T_v$ in the driving ($x$) direction is simplified as shown in Figure 3. That is

$$
T_v = T_a + 44.0 \quad (0 \leq x_v^* \leq 0.2) \\
T_v = T_a + 25.9 \quad (0.2 \leq x_v^* \leq 0.4) \\
T_v = T_a + 20.3 \quad (0.4 \leq x_v^* \leq 1.0)
$$

(13)

where $x_v^*$ is the normalized distance ($= x_v / L_{vh}$, $L_{vh}$: vehicle length, $x_v$: distance from the vehicle front).

Figure 2. Correlation of predicted and measured tire temperatures.

Figure 3. Spatial variation of bottom surface temperature of vehicle in $x$ direction.
$S_{va}$ is given by Newton’s law of cooling as

$$S_{va} = \alpha_s \left(T_a - T_{ps}\right)$$

(14)

In this case, $\alpha_s$ is calculated by inserting the vehicle-induced wind velocity, $V_w$ (m/s) instead of $V_{ws}$ in Eq. (6).

Figure 4 shows the time variation of $V_w$ for different vehicle speeds, $V_v$. During acceleration, $V_w$ increases with time linearly;

$$V_w = at \quad (0 \leq t \leq t_{v_{\text{max}}})$$

(15)

where $t_{v_{\text{max}}}$ is elapsed time when $V_w$ reaches a maximum, $V_{w_{\text{max}}}$.

For the deceleration period, $V_w$ is reduced with time as follows:

$$V_w = V_{w_{\text{max}}} \exp\left\{-b\left(t - t_{v_{\text{max}}}\right) - c\left(t - t_{v_{\text{max}}}\right)\right\}\quad\left(t_{v_{\text{max}}} \leq t \leq t_{v_0}\right)$$

(16)

where $t_{v_0}$ is elapsed time when $V_w$ becomes zero again. Coefficients, $a$, $b$, $c$ and the parameters, $V_{w_{\text{max}}}$, $t_{v_{\text{max}}}$ and $t_{v_0}$ in Eqs. (15) and (16) are given by the following functions of $V_v$, respectively.

$$a = 0.08V_v$$

(17)

$$b = 0.28 \times 10^{-2}V_v + 0.13$$

(18)

![Figure 4. Time variation of vehicle-induced wind velocity, $V_w$, for different vehicle speeds, $V_v$.](image-url)
\[ c = V_{\text{wmax}} \exp\left(-b(t_{v0} - t_{\text{vmax}})\right)/(t_{v0} - t_{\text{vmax}}) \]  
\[ V_{\text{wmax}} = 0.08V_v \]  
\[ t_{\text{vmax}} = 1.2 \exp\left(-0.3 \times 10^{-2}V_v\right) \]  
\[ t_{v0} = -1.4 \times 10^{-2}V_v + 7.6 \]

**OBSERVATION**

Figure 5 (a) and (b) are an isothermal distribution of the road surface temperature measured in Fukui city at 19:00 on December 8th, 2009 and its video picture, respectively. A traffic light is located on the bottom side of the picture. Therefore, the vehicles stop and go are repeated on the right half of the roadway (Road-R), while the vehicles stop and go do not occur on the left half (Road-L). The road surface temperature in the vehicle-passage area of the Road-R (indicated by \(A\)) is higher than that in the non vehicle-passage area (indicated by \(B\)). We define the difference in the road surface temperature between the vehicle-passage area and the non vehicle-passage area as \(\Delta T_{ps}\) (°C) in this paper. Actually, \(\Delta T_{ps}\) between \(A\) and \(B\) was about 3.5°C. The same tendency can be observed on the Road-L too (see the road surface temperatures of two areas, \(C\) and \(D\)). \(\Delta T_{ps}\) (°C) between \(C\) and \(D\) was about 1.0°C. This is attributed to the tire frictional heat and the vehicle radiant heat. Comparing the road surface temperatures of two areas, \(A\) and \(C\), it is seen that the former is higher than the latter. This temperature difference may be caused by the increase in the vehicle radiant heat associated with the vehicles stop.

![Figure 5](image-url)  
(a) Thermographic image                       (b) Video picture

**Figure 5. Isothermal distribution of road surface temperature near a traffic light**  
(at 19:00 on December 8th, 2009, Fukui city, Japan).
NUMERICAL CONSIDERATION ON EFFECT OF VEHICLE HEATS ON ROAD SURFACE TEMPERATURE

SIMULATION CONDITION

Model Assumptions
1) The frequency of vehicle passage is constant and is calculated from hourly traffic volume.
2) The vehicle speed is constant over an observation period.
3) Vehicles all pass over the same track within a lane.
4) All vehicles have the same size of $L_{vh} (= 4.0 \text{ m})$.

Simulation Conditions
Three different simulation conditions were investigated: Case-0: no vehicle, Case-1: a road without a traffic light, and Case-2: a road with a traffic light.

Table 1 shows the weather and traffic conditions for the numerical simulations. The computations simulated a 24 hour period starting at 6:00. The time increment of the computation, $\Delta t$, was one minute. The assumed diurnal variations of atmospheric temperature, $T_a$, and relative humidity, $RHa$, and of short and long-wave radiation, $R_{sd}$ and $R_{ld}$, are given in Figures 6 and 7, respectively. The value of $V_{ws}$, was fixed at 2 m/s.

Traffic frequency, $F_t$, (number of vehicles/h) was assumed to be 480 in the time period of 6:00-20:00 (TZ-1) and 120 during the period of 20:00-6:00 next day (TZ-2). $V_v$ was constant at 20 km/h for both Case-1 and Case-2. The assumed vehicle stop and go periods at the traffic light, $t_{vs}$ (min) and $t_{vm}$ (min), were 1 and 5 min, respectively throughout the day for Case-2.

Table 1. Weather and traffic conditions for numerical simulations.

<table>
<thead>
<tr>
<th>Weather condition</th>
<th>Wind velocity</th>
<th>Solar radiation and sky radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>As shown in Figure 6</td>
<td>2 m/second (constant)</td>
<td>As shown in Figure 7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traffic condition</th>
<th>Simulation</th>
<th>Traffic volume $F_t$</th>
<th>Vehicle speed $V_v$</th>
<th>Stop time $t_{vs}$ / go time $t_{vm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-0</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case-1</td>
<td>480 vehicles/hour (6:00-20:00), 120 vehicles/hour (20:00-6:00)</td>
<td>20 km/hour</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Case-2</td>
<td>480 vehicles/hour (6:00-20:00), 120 vehicles/hour (20:00-6:00)</td>
<td>20 km/hour</td>
<td>1 minute / 5 minutes</td>
<td></td>
</tr>
</tbody>
</table>
SIMULATION RESULTS

Vehicle related heat fluxes

Figure 8 shows the diurnal variations of the ratio (P) of the vehicle heat fluxes (St, Rv, Sva and Qv) to total heat flux across the road surface, QA (= |G| + |Rld| + |Rsd| + |Rsu| + |Sa| + |L| + |St| + |Rv| + |Sva|), where | | means an absolute value. The value of P is given by the following equation.

\[
P = \frac{S_t \text{ or } R_v \text{ or } S_{va} \text{ or } Q_v}{Q_a}
\]  

Positive or negative P contributes to a rise or fall of Tps, respectively.

PSl (= St/Qa) and PRv (= Rv/Qa) were always positive, while PSva (= Sva/Qa) was always negative because of the fact, Ta < Tps. PQv (= Qv/Qa) varied from 0.07 to 0.12 during the time period TZ-1 but was about 0.03 for the whole of period TZ-2.
Figure 8. Diurnal variations of ratio of vehicle heat fluxes to total heat flux across road surface (Case-1).

Road surface temperature
Figure 9 (a) and (b) show the diurnal variations of $T_{ps}$ for Case-1 (without a traffic light) and Case-2 (with a traffic light), respectively, along with that for a dry road, Case-0. Comparing $T_{ps}$ of Case-0 with that of Case-1 or Case-2, it is seen that the former is relatively high for the daytime and relatively low for the nighttime. Shade made by the vehicle causes the lowering of $T_{ps}$, while the vehicle heat inputs contribute to the rise of $T_{ps}$.

$T_{ps}$ of Case-2 is changed in wavelike fashion due to the difference in the vehicle heat fluxes between the vehicle stop and go times. $T_{ps}$ rises during the vehicle stop time because of $S_t$, while $T_{ps}$ falls during the vehicle go time. $S_t$ of 300 W/m$^2$ (not shown in this paper) is intermittently supplied to the road surface in the periods of 6:00-8:00 and 21:00-6:00, so that the amplitude of $T_{ps}$ becomes 2°C.

We try to compare the simulated $\Delta T_{ps}$ for Case-1 (without a traffic light) and Case-2 (with a traffic light) with the observed one shown in Figure 5. The Road-L and Road-R in Figure 5 correspond to a road for Case-1 and Case-2, respectively. The calculated $\Delta T_{ps}$ at 19:00 for Case-1 was about 1.5°C, while the observed $\Delta T_{ps}$ between (A) and (B) of the Road-L in Figure 5(a) was about 1.0°C. The calculated $\Delta T_{ps}$ at 19:00 for Case-2 ranged from 1.5°C to 4.0°C, while the observed $\Delta T_{ps}$ between (A) and (B) of the Road-R was about 3.5°C. It is seen that the calculated $\Delta T_{ps}$ was nearly the same as the observed $\Delta T_{ps}$, regardless of the traffic light.

Figure 9 (b) shows the danger of refreezing of road surface attributed to the vehicle heat fluxes. $T_{ps}$ below the freezing point starts rising from 19:00 and then fluctuates about the freezing point (see an enlarged view in Figure 9 (b)). This phenomenon is called
“zero-crossing” in this paper. The zero-crossing occurred in the morning 8:00-8:40 and in the evening 19:00-23:00, respectively.

Although this numerical result was obtained for a dry road surface, it is inferred that the ‘zero-crossing’ would cause melting and refreezing of snow and ice on the road surface and would lead to the occurrence of ‘black ice’.

**CONCLUSIONS**

The influence of the vehicle related heat fluxes on the road surface temperature for a road with a traffic light was investigated through a field observation and numerical simulations. Numerical simulations were performed by changing the stop and go times of vehicles at a traffic light.
The main conclusions drawn from this study are as follows.

1. The thermography observation showed that the influence of the vehicle heats on the road surface temperature can not be disregarded.
2. The VRFF model was able to reproduce the change of road surface temperature due to vehicle related heats.
3. The contribution of the tire frictional heat to the heat budget on the road surface becomes more significant for a road with a traffic light.
4. The ratio of the vehicle related heat fluxes to total heat flux across the road surface reached about 12% at most.
5. Under vehicles stop and go the road surface temperature oscillated through about 2°C associated with the vehicle related heat fluxes. The fluctuation of road surface temperature about the freezing point, ‘zero-crossing’, was appeared in the nighttime from the present simulation.
6. It can be inferred from the ‘zero-crossing’ that the repetition of melting and refreezing of the ice surface on a road induces the occurrence of ‘black ice’.

REFERENCES