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Research on Short Term Prediction Algorithm for Freeway Pavement Ice

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Abstract: This article focuses on the short-term prediction algorithm for ice condensation on highway pavement. Solar radiation, ground long wave radiation, and atmospheric inverse radiation are the main factors affecting road surface temperature changes. According to the principle of radiation heat transfer, there is a radiation balance relationship among these three factors. Therefore, based on the balance relationship between these three radiations and the physical heat formula, this article designs a short-term prediction algorithm for road icing. Based on the basic theory of radiation heat transfer, the energy balance between solar shortwave radiation, atmospheric inverse radiation, and ground longwave radiation is calculated to predict the temperature of highway road surfaces.

Keywords: Freezing ice; Short term prediction algorithm, Radiative heat transfer, Expressway pavement temperature.

1. Short Term Prediction Algorithm Under Freezing Conditions

1.1. Basic Theory of Radiation Heat Transfer

Any object continuously emits radiation energy outward and absorbs the radiation energy emitted by nearby objects, while converting this radiation energy into thermal energy. The exchange process between the radiation energy of these objects is called radiative heat transfer. The process of radiative heat transfer is often seen in reality, such as the sun shining on the ground, using a stove to heat in winter, freezing mountains and rivers for thousands of years, and various liquids and gases. As long as the temperature of an object is not absolute zero, it will radiate heat and radiation to the surrounding area. During the process of any object emitting and absorbing thermal radiation, its temperature will change with this process. That is to say, what thermal radiation ultimately changes is the temperature of the object itself. As shown in Figure 1, the process of absorbing, reflecting, and transmitting radiation energy by an object is as follows:

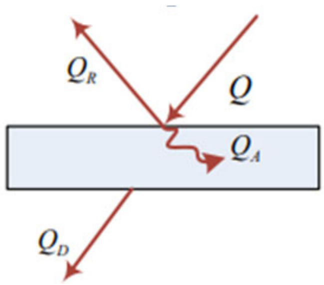

Figure 1. Radiative heat transfer process

In Figure 1, it can be seen that Q represents the total radiation energy (w/m^2), Q_A represents the absorbed radiation energy (w/m^2), Q_R represents the reflected radiation energy (w/m^2), and Q_D represents the transmitted radiation energy (w/m^2). Therefore, according to the radiation balance principle, it can be concluded that:

$$Q_A + Q_R + Q_D = Q \tag{1}$$

$$\frac{Q_A}{Q} + \frac{Q_R}{Q} + \frac{Q_D}{Q} = 1 \tag{2}$$

In the equation:

$A = \frac{Q_A}{Q}$ is the absorption rate

$R = \frac{Q_R}{Q}$ is the reflectivity

$D = \frac{Q_D}{Q}$ is the transmittance, then:

$$A+R+D=1 \tag{3}$$

If A=1 in equation (3), it means that the object has absorbed all the radiant energy. At this time, the transmissivity and emissivity are all 0. The object with an absorptivity of 1 is called a blackbody. If R=1 in equation (3), it indicates that the object can fully reflect radiation energy, and at this point, the transmittance and absorption are all 0. This type of object with a reflectivity of 1 is called a mirror. If D=1 in equation (3), it means that the object can transmit all the radiation energy, and at this point, the reflectivity and absorption are all 0. This type of object with a transmittance of 1 is called a permeable body.

Blackbody is the standard object for studying thermal radiation in physics. It can absorb all electromagnetic waves radiated from the outside without any transmission or reflection. Stephen Boltzmann's law proposed the relationship between the surface temperature of a blackbody and its radiation ability as follows:

$$E = \varepsilon_0 E_b = \varepsilon_0 \sigma T^4 \tag{4}$$

In the formula, E is the radiation capacity of the gray body (w/m^2); ε_0 is the blackness of an object, which depends on its properties and surface condition. It is generally measured experimentally and its value varies between 0 and 1.

1.2. Short term prediction algorithm for road icing

Solar radiation, ground long wave radiation, and atmospheric inverse radiation are all forms of thermal radiation. Solar radiation is a flow of particles and electromagnetic waves emitted by the sun. After the ground absorbs solar radiation, it causes an increase in ground temperature, and solar radiation is the main driving force that causes an increase in ground temperature. Ground long wave radiation is the long wave radiation that is absorbed by the sun on the ground and then emitted into the atmosphere. Therefore, ground long wave radiation can cause heat loss on the ground, and ground long wave radiation is the main factor leading to a decrease in ground temperature. Atmospheric reverse radiation is the phenomenon of the atmosphere radiating energy outward after absorbing long-wave radiation emitted from the ground. Its action on the ground also leads to an increase in ground temperature. Solar radiation, ground long wave radiation, and atmospheric inverse radiation are the main factors affecting road surface temperature changes. According to the principle of radiation heat transfer, there is a radiation balance relationship among these three factors. Therefore, based on the equilibrium relationship between these three radiations and the physical heat formula, this chapter designs a short-term prediction algorithm for road surface icing, which is used to predict road surface temperature. According to the principle of radiation heat transfer, the equilibrium relationship between the three can be obtained as shown in Figure 2.

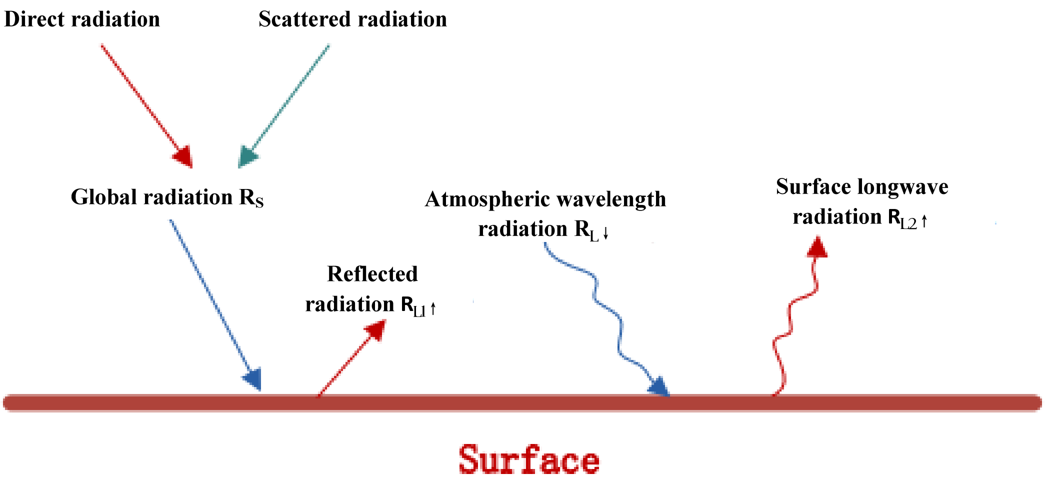

Figure 2. Principle of Ground Net Radiation

In Figure 2, R_S(w/m^2)represents solar radiation; $R_{L\downarrow}$(w/m^2)is the longwave radiation emitted downward from the atmosphere, which is called atmospheric inverse radiation; $R_{L1\uparrow}$represents the atmospheric inverse radiation reflected from the ground; $R_{L2\uparrow}$ represents the longwave radiation emitted upwards from the ground; The sum of the atmospheric inverse radiation reflected from the ground and the longwave radiation emitted upwards from the ground is called the net longwave radiation on the surface, denoted as $R_{L\uparrow}$(w/m^2). Therefore, based on the radiation balance principle between solar radiation, atmospheric inverse radiation, and surface net longwave radiation, the ground absorbed net radiation R_n can be obtained as:

$$R_n = R_{S\downarrow}(1-\alpha) + R_{L\downarrow} - R_{L\uparrow} \quad (5)$$

In the equation, α Is the albedo of the road surface, whose value is constant 0.31.

According to formulas (3) and (4), it can be seen that the radiation ability of an object is affected by its surface temperature. Therefore, the calculation formula for atmospheric reverse radiation $R_{L\downarrow}$ at a temperature of T_a is as follows:

$$R_{L\downarrow} = \varepsilon_0 \sigma T^4 \quad (6)$$

Weng Duming et al. conducted research on atmospheric inverse radiation and fitted it using radiation and sounding data. The calculation formula for atmospheric inverse radiation $R_{L\downarrow}$ was obtained as follows:

$$R_{L\downarrow} = \sigma T_a^4[0.536 + 0.128\ln(1+e_d)](1+0.145n^2)(7)$$

In the equation:

T_a is the air temperature, expressed in k;

e_d is the water vapor pressure (hPa);

n is the cloud cover.

Due to the close relationship between atmospheric reverse radiation and air temperature and water vapor pressure. The atmospheric reverse radiation part $R_{L1\uparrow}$ reflected from the ground and the longwave radiation $R_{L2\uparrow}$ emitted upwards from the ground are respectively:

$$R_{L1\uparrow} = (1-\varepsilon_s)R_{L\downarrow} \quad (8)$$

$$R_{L2\uparrow} = \varepsilon_s \sigma T_s^4 \quad (9)$$

Then, the net long wave radiation on the surface is denoted as $R_{L\uparrow}$ as:

$$R_{L\uparrow} = \varepsilon_s \sigma T_s^4 + (1-\varepsilon_s)R_{L\downarrow} \quad (10)$$

In the formula, Ts is the ground temperature (k); $\varepsilon_s$is the surface specific radiance, which is generally between 0.85-0.99, and the surface specific radiance of asphalt pavement is 0.96.

Due to the physical heat formula:

$$Q = cm\Delta T \quad (11)$$

Therefore, from (11) and formulas (5) to (10), the change in road surface temperature after the time interval Δt is obtained as ΔT:

$$\Delta T = \frac{Q}{c_p m_p} = \frac{R_n S_p \Delta t}{c_p m_p} = \frac{R_n \Delta t}{c_p \rho_p h_p} \quad (12)$$

In the formula, Q is the heat (J); c_p is the specific heat capacity of asphalt pavement, and the value is 1.67kJ/kg • ℃; m_p is the mass (kg);

ΔT is the temperature change value (℃); Δt is the interval time (s); S_p is the area of heat absorption (m^2); ρ_p is the density of asphalt pavement, with a value of $1.25 \times 10^3 kg/m^3$; h_p represents the calculated depth of the road surface, taken as 0.01m here.

If T_0 is the road surface temperature at the current time and T_1 is the road surface temperature at the next time, then:

$$T_1 = T_0 + \Delta T \quad (13)$$

2. Verification of Ice Warning Algorithm

According to the above algorithm, the prediction time is set, combined with the meteorological data collected by the system's road meteorological station. At the same time, the road surface freezing temperature is obtained through experiments on the freezing detection lower computer, and then the short-term freezing prediction algorithm is used to predict the road surface temperature. The relevant data is shown in Table 1.

Table 1. Short term prediction data of freezing

No.	Current time	Prediction time	Current temperature ℃	Current road surface temperature ℃	Solar radiation w/m^2	Freezing temperature ℃
1	10:00	10:30	-2.0	-1.4	268	-4.7
2	13:10	13:30	3.1	2.5	333	-6.8
3	18:00	18:50	1.3	1.1	0	-6.1
4	20:40	21:00	-3.6	-3.1	0	-4.6
5	23:00	24:00	-5.8	-5.0	0	-5.9

In Table 1, the prediction time intervals are set to be 30min, 20min, 50min, 20min, and 60min, respectively. According to the short-term prediction algorithm for ice formation, the corresponding predicted road surface temperatures can be calculated to be 1.5, 3.9, -2.7, -4.8, and -6.2, respectively. Therefore, by comparing the predicted road surface temperature with the road surface ice formation temperature, it is expected that at 10:30, 13:30, and 18:50, when the road surface temperature is higher than the ice formation temperature, the road surface will not ice formation; At 21:00 and 24:00, if the road surface temperature is lower than the freezing temperature, the road surface will experience freezing.

3. Summary

This article conducts a detailed study on the algorithm and model for ice freezing warning. By analyzing the influencing factors of road icing and applying the basic theory of radiation heat transfer, the balance relationship between solar short wave radiation, atmospheric inverse radiation, and ground long wave radiation was studied. On this basis, a short-term prediction algorithm of road freezing is proposed, and the finite state machine model of road freezing early warning is established by dividing the system states and combining the finite state automata theory theory. Finally, the ice freezing warning algorithm was validated based on the monitoring data of the road meteorological station.

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