Wide-area Rail Temperature Prediction Method Using GIS Data

Fumihiro URAKAWA  Tsutomu WATANABE  Shigekatsu KIMURA
Track Dynamics Laboratory, Railway Dynamics Division

Track temperature and axial force can vary because of the influence of shadow cast by geographical features near railway lines. However, exactly how these variations affect track buckling has not yet been clarified. In this paper, the rail temperature distribution of the track is calculated in consideration of shadows cast by geographical features using a rail temperature prediction model. Results from these investigations confirmed that this method of analysis could reproduce drops in rail temperature of between 10°C and 15°C, which corresponds to the rail temperature difference actually observed in shaded and sunny areas.

Keywords: rail temperature distribution, shade of the geographic features, GIS, track buckling, solar radiation analysis

1. Introduction

Track buckling stability of long rails is important for ballasted track maintenance. In Japan, track buckling stability is evaluated by monitoring predicted rail temperature rises and changes in temperature in relation to the track buckling strength calculated on the basis of the rigidity and shape of the track. Variations in rail temperature and axial force on actual railway lines can be assumed to be due to shadows cast on the line by geographic features (terrain and buildings). However, the current management method assumes uniform rail temperature and axial force for certain sections. In addition, the effect of rail temperature variations is not taken into consideration in the theoretical formula used for calculating buckling strength [1, 2] and buckling stability analysis [3, 4, 5]. This is due to the difficulty in monitoring constantly moving shade and accompanying changes in rail temperature and axial force distribution with sufficient accuracy for practical use. In reality however, rough evaluations are widely used in current management methods in railway operators. Nevertheless, if track buckling stability could be evaluated in consideration of falls rail temperature and axial force due to shade, it could help reduce management costs.

In other fields, such as photovoltaic power generation design and road surface temperature control, solar radiation distribution considering shade cast by the surrounding landscape, is estimated from solar radiation analyses using geographic information system data (GIS data) [6]. The authors developed a model, referring to previous research [7, 8], that predicts rail temperature from the amount of solar radiation in the area where the track is, as a method for grasping the distribution of rail temperature over a wide area [9]. The developed model should make it possible to estimate the maximum rail temperature during the daytime in unshaded areas within an error of 2°C [10]. This model should make it possible to reproduce rail temperature and axial force distribution in detail, by applying solar radiation distribution in question, whilst considering shadows thrown by surrounding features.

This study describes the development of a method that can predict rail temperature distribution over a wide area taking into account shade from surrounding features. This rail temperature prediction method model applies solar radiation analysis using GIS data. In addition, in order to understand the distribution characteristics of rail temperature in areas shaded by buildings, etc., and to verify the validity of the developed method, rail temperatures were measured in both shaded and sunny spots during the daytime.

2. Rail temperature prediction model considering shadow cast by geographic features

In this paper, the time axis is \( t \) and the position in the longitudinal direction of the rail is \( x \). Figure 1 shows the calculation flow for predicting rail temperature. First, solar radiation in the area where the rail is located (normal direct radiation \( I_{dn}(x,t) \) and horizontal diffuse radiation \( I_{dh}(x,t) \)) is calculated taking into account shadows from buildings, from the solar radiation analysis using the GIS data (topography, build-

![Fig. 1 Calculation flow of rail temperature prediction considering the shadow of the geographic features]
ings, track data) shown in Fig. 2. Next, the heat flow rate \( Q_{\text{air}}(x, t) \) absorbed by the rail is calculated from the amount of solar radiation and the geometric shape of the rail. After specifying the initial rail temperature, the heat flow rate \( Q_{\text{air}}(x, t) \) discharged from the rail is calculated from the rail temperature. Then, a heat conduction equation is solved for an arbitrary time \( t \) to calculate the rail temperature after the time \( \Delta t \). This is repeated for an arbitrary time \( t \) to calculate the rail temperature for position \( x \). Details are described below.

### 2.1 Solar radiation analysis using GIS data

The “Points Solar Radiation” analysis tool, one of the ArcGIS Spatial Analyst (ESRI-Japan Co., Ltd.) extensions, was used to calculate solar radiation. With this analysis tool, the horizontal direct radiation \( I_{\text{dn}}(x, t) \) and horizontal diffuse radiation \( I_{\text{dh}}(x, t) \) at the point data position can be calculated from the DSM (Digital Surface Model: numerical elevation data including the height of buildings and trees) data and the point data. Direct radiation is the energy per unit area of solar radiation that is scattered and reflected by atmospheric components, and arrives from all directions from the sky. Direct radiation received on the horizontal plane is called horizontal direct radiation, diffuse radiation received on the horizontal plane is horizontal diffuse radiation, and direct radiation received on the plane perpendicular to the sunlight is called normal direct radiation. Solar altitude \( h(x, t) \) which is the angle between the horizontal plane and sunlight can be obtained from the position (longitude, latitude) of the point data and the date and time. Finally, using \( h(x, t) \) and (1), the horizontal direct radiation \( I_{\text{dn}}(x, t) \) can be converted to the normal direct radiation \( I_{\text{dn}}(x, t) \) as shown in Fig. 3.

\[
I_{\text{dn}}(x, t) = \frac{I_{\text{dn}}(x, t)}{\sin h(x, t)}
\]  

(1)

In the rail temperature prediction, the normal direct radiation \( I_{\text{dn}}(x, t) \) and the horizontal diffuse radiation \( I_{\text{dh}}(x, t) \) are calculated by using the point data arranged along the track data as shown in Fig. 2.

### 2.2 Rail temperature prediction method using the solar radiation

#### 2.2.1 Calculation of heat flow rate absorbed by the rail

The heat flux absorbed from the rail was calculated considering the heat fluxes as shown in Fig. 4 (a): (i) direct radiation \( I_D(l, x, t) \) obtained from (2); (ii) diffuse radiation \( I_D(l, x, t) \) obtained from (3); (iii) ground-reflected radiation \( I_R(l, x, t) \) obtained from (4); (iv) atmospheric radiation \( R_{\text{atm}}(l, x, t) \) obtained from (5); and (v) ground radiation \( R_{\text{ground}}(l, x, t) \) obtained from (6).

\[
I_D(l, x, t) = CS(l, x, t)I_D(x, t)(\sin h(x, t)\cos \beta(l, x) + \cos h(x, t)\sin \beta(l, x)\cos \psi(x, t))
\]

(2)

\[
I_R(l, x, t) = \frac{1 + \cos \beta(l, x)}{2}I_R(x, t)
\]

(3)

\[
I_R(l, x, t) = \frac{1 + \cos \beta(l, x)}{2}(I_{\text{dn}}(x, t) + I_{\text{dh}}(x, t))
\]

(4)

\[
R_{\text{atm}}(l, x, t) = \frac{1 + \cos \beta(l, x)}{2}R_{\text{atm}}
\]

(5)

\[
R_{\text{ground}}(l, x, t) = \frac{1 - \cos \beta(l, x)}{2}e_r \sigma \cdot (T_{\text{air}}(x, t) + 273.15)^4
\]

(6)

Where, \( CS(l, x, t) \) is the parameter that represents the rate of sunlight on the rail surface \( 0 \leq CS \leq 1 \), as shown in Fig. 5; \( \beta(l, x) \) is slope of the rail tangent plane from the horizontal plane; \( \psi(x, t) \) is relative azimuth between the sun and the rail (Fig. 3 (a)); \( \rho \) is reflectance on the ground surface; \( R_{\text{atm}} \) is downward infrared radiation; and \( e_r \) is Infrared
emissivity on the ground surface, \( \sigma \) is the Stefan-Boltzmann constant; and \( T_{GS}(x,t) \) is ground surface temperature, \( ^\circ C \).

The heat flow rate absorbed by the rail per unit length \( Q_{in}(x,t) \) is obtained from (7), that is line integration of the sum of (i) to (viii) multiplied by emissivity of the rail surface \( \varepsilon_R \) along the rail cross-sectional shape \( L_c \).

\[
q_{in}(l, x, t) = I_0(l, x, t) + I_1(l, x, t) + I_2(l, x, t) + R_s(l, x, t) + R_4(l, x, t) + R_5(l, x, t)
\]

\[
Q_{in}(x,t) = \int_{L_c} \varepsilon_R q_{in}(l, x, t) dl
\] (7)

2.2.2 Calculation of heat flow rate discharged by the rail

The heat flux discharged from the rail was calculated considering the heat fluxes as shown in Fig. 4(b): (vi) heat conduction to sleepers \( J_c(l, x, t) \) obtained from (8); (vii) convective heat transfer to air \( J_l(l, x, t) \) obtained from (9); and (viii) radiant heat \( J_r(l, x, t) \) from the rail obtained from (10).

\[
J_c(l, x, t) = -\frac{\lambda_R}{2L_p} T_l(x,t) - T_{R}(t)
\] (8)

\[
J_l(l, x, t) = \alpha(x,t)(T_{GS}(x,t) - T_l(x,t))
\] (9)

\[
J_r(l, x, t) = \varepsilon_R \alpha \cdot (T_l(x,t) + 273.15)^4 - \frac{\lambda_R}{2L_p} T_l(x,t) - T_{R}(t)
\] (10)

where, \( \lambda_R \) is thermal conductivity of the rail pad; \( L_p \) is thickness of the rail pad; \( T_l(t) \) is air temperature; \( C \); and \( T_l(x,t) \); rail temperature, \( ^\circ C \).

Note that (8) includes an approximate equation that temperature at the bottom surface of the track pad is \( (T_{R}(x,t) + T_{GS}(x,t))/2 \), which was obtained from the measurement results of the rail temperature, sleeper top temperature, and air temperature in a previous study. In [9], the heat transfer coefficient \( \alpha(x,t) \) between the rail and air in [9] was modeled by natural convection assuming a windless condition where the rail temperature tends to rise. However, in this paper, it was modeled with forced convection in order to support temperature prediction over a wider range of wind speed conditions. At that time, the empirical formula [11] of laminar heat transfer of forced convection of the flat plate was applied to the rail, and it was calculated by (11). The validity of this modeling is confirmed in [10].

\[
\alpha(x,t) = 0.644Pr^{0.15}(\frac{v_a(t)}{v_R})^{0.5}
\] (11)

where, \( Pr \) is Prandtl number of air; \( v_a \) (t) is wind speed; \( L_R \) is representative length of the rail; and \( v \) is kinematic viscosity coefficient of air.

The heat flow rate discharged by the rail per unit length \( Q_{out}(x,t) \) is obtained from (12), that is line integration of the sum of (vii) to (viii) along the rail cross-sectional shape \( L_c \).

\[
Q_{out}(x,t) = \int_{L_c} (J_c(l,x,t) + J_l(l,x,t)
\]

\[
+ J_r(l,x,t)) dl
\] (12)

Further, on the jaw (Surface1 in Fig. 4), abdomen (Surface2 in Fig. 4), and upper side of the bottom (Surface2 in Fig. 4) of the rail surface, the absorbed heat \( Q_{in} \) and the discharged heat \( Q_{out} \) are corrected in consideration of heat exchange that the reflected heat flux and the radiant heat flux on one surface are absorbed again by the other two surfaces. See [9] for more information.
is the longitudinal direction of the rail. The test location was a ballasted track in a straight section with continuous welded rail, with JIS 60kg rails. The test date was January 21, 2019, and the weather in the location was fine. In order to measure the rail temperature distribution, thermocouples (T-FFF (M), Fukuden) were attached to the field corner (FC) side rail web in 10 measurement positions (S1 to S10). The temperatures were measured at intervals of about 20 m, as shown in Fig. 7 (b). In addition, the air temperature and the wind speed used for the prediction of the rail temperature were measured by a weather station (VantagePro2, manufactured by DAVIS) which was installed near point S1 at 1 m height from the ground. The measurement results are shown in Fig. 8. The maximum air temperature on the test day was 10 °C, and the maximum wind speed was 3.1 m/s.

3.2 Prediction method and conditions

3.2.1 Solar radiation analysis

Figure 9 (a) shows the DSM data and track point data used in the solar radiation analysis and Fig. 9 (b) shows the original data for creating these data. The mesh size of the DSM data and the interval of the line point data were 1 m. The DSM data to be input to the solar radiation analysis were created by converting the building polygon data into elevation data and adding it to the DEM data (digital elevation model that does not include the height of buildings, etc.). At that time, the data L_BLD of *ArcGIS Geo Suite* (ESRI-Japan Co., Ltd.) was used for the polygon data of the building. In addition, as shown in Fig. 9 (b), polygon data (height 1.5 m) of the wall was manually created and added using a GIS software (*ArcGIS Pro*). The DEM data used for the analysis was the digital elevation model of the 5 m mesh (DEM5A) provided by the Geospatial Information Authority of Japan was converted to the 1 m mesh. As shown in Fig. 9 (b), the track point data was created from the track line data L_RROAD of *ArcGIS Geo Suite*.

Solar radiation on January 21, 2019 of the measured points was calculated at intervals of 0.25 hour by inputting the data in Fig. 9 (a) into the "Points Solar Radiation" analysis tool. Assuming fine weather, the following analysis parameters were set: atmospheric transitivity 0.7 and diffuse proportion (the proportion of diffuse radiation in the global solar radiation) 0.3. The diffuse model type was "Uniform sky" (the incoming diffuse radiation is the same from all directions in the sky). Figure 10 shows the analysis results of the normal direct radiation $I_{DN}$ and the horizontal diffuse radiation $I_{DH}$ around the rail temperature measurement point. The figure on the left shows the distribution in the x direction at 11:00, 13:00, and 15:00, and the figure on the right shows the time history waveforms at points S6 ($x = 285$ m) and S8 ($x = 325$ m). From the figures, the amount of solar radiation at 200 m < $x$ < 240 m and 290 m < $x$ is smaller than the others. The former is the location shaded by Bldg. 1 whereas the latter is in the shadow of Bldg. 3 and the wall. The analysis expresses a decrease in the amount of solar radiation due to these shaded areas.
3.2.2 Rail temperature prediction

The heat flow rate absorbed by the rail was obtained from the normal direct radiation $I_{dn}$ and the horizontal diffuse radiation $I_{dn}$ in the previous section, and the predicted value of the rail temperature distribution was calculated from heat conduction analysis. Table 1 shows the parameters used in the calculation. Assuming an oxidized surface, we set the emissivity of the rail surface to 0.8. The ground surface temperature, in the same way as with the rail temperature prediction. The representative length $L_R$ of the rail can take various values depending on factors such as the wind direction. In tests conducted in [10], when $L_R = 0.5$ m, the measured rail temperature and the predicted rail temperature were in good agreement, thus we used this parameter. For the downward infrared radiation $R_0$, the average value during fine weather in winter was used. The initial rail temperature was 2.7 °C, which is the same as the air temperature at sunrise. The analysis time increment $\Delta t$ of the heat conduction analysis was 0.25 hours (900 seconds), and the spatial increment $\Delta x$ was 1 m, which is the same as the point data pitch of the line.

### Table 1 Parameters for rail temperature prediction

| Parameter                                      | Value       |
|------------------------------------------------|-------------|
| Emissivity on the rail surface $\varepsilon_R$ | 0.8         |
| Stefan–Boltzmann constant $\sigma$            | 5.67 x 10^{-8} W/(m²K) |
| Reflectance on the ground surface $\rho_e$     | 0.3         |
| Downward infrared radiation $R_0$             | 0.8 MJ/(m²h) |
| Infrared emissivity on the ground surface $\varepsilon_E$ | 0.95 |
| Thermal conductivity of the rail pad $\lambda_P$ | 0.25 W/(mK) |
| Thickness of the rail pad $L_P$                | 0.01 m      |
| Representative length of the rail $L_R$        | 0.5 m       |
| Prandtl number of air $Pr$                     | 0.7         |
| Density of the rail steel $\rho_R$             | 7820 kg/m³  |
| Specific heat of the rail $c_R$                | 461 J/(kgK) |
| Thermal conductivity of the rail $\lambda_R$   | 50 W/(mK)   |
| Cross-sectional area of the rail $A_S$         | 0.00775 m²  |
| Air temperature $T_a$                         | Fig. 8      |
| Wind speed $v_a$                               | Fig. 8      |
| Kinematic viscosity coefficient of air $\nu$   | 14 μm²/s    |

3.3 Test results

Figure 12 shows a comparison between the measured and predicted values of the rail temperature distributions from 10:00 to 15:00. As shown in the figure, at 12:00, 14:00, and 15:00, the measured value at measuring points S4 and S5 have a large difference from the measured and predicted values of surrounding points. There is a level crossing of 6.5 m wide at $x = 256$ m between S4 and S5, and the heat balance conditions differ around there. This is probably the cause of these differences. The rail temperature distributions in other locations generally showed agreement between the measured and predicted values. At 14:00 when the rail temperature peaked, the rail temperatures were about 10 °C lower than the surrounding sunny locations at measuring points S2 and S3, which were shaded by Bldg. 1. Also, at the measuring points S7 to S10, which were in the shadow of Bldg. 3 and the wall, the rail temperatures were about 15 °C lower than the surrounding sunny locations. Figure 12 shows that the predicted values successfully reproduced tendencies in rail temperature distribution, including differences between sunny and shaded areas. The observed temperature drops at measuring points S2, S3, and S7 to S10 due to shade from buildings had not been reproducible using the prediction method of previous studies [7]. Using solar radiation distribution and taking into account the shade from surrounding buildings to predict rail temperature was found to greatly improve the consistency.
of the predictions with actual rail temperature. Field tests confirmed the validity of the developed rail temperature prediction model.

4. Conclusions

In order to clarify areas shaded by buildings and the effect of these shadows on rail temperature and axial force distribution, we developed a new model that predicts rail temperature distribution using solar radiation distribution calculated from the elevation data of geographic features. In addition, to verify the accuracy the developed model, rail temperatures were measured on an actual track and compared with predicted values. The obtained findings are as follows:

・The validity of the developed rail temperature prediction model was confirmed by comparing predicted rail temperatures with actual measured temperatures from an actual track.
・In winter measurements, the rail temperature decreased by 10°C to 15°C in locations shaded by nearby buildings, compared to sunny locations.
・The developed model successfully reproduces the rail temperature distribution on actual tracks, including drops of rail temperature in the shade.

In this paper, we focused on the effect of shade on rail temperature, but the developed method can also convert various weather conditions into rail temperature. Therefore, we plan to conduct the following studies in the future.

(1) Prediction of the maximum rail temperature in summer considering regional characteristics from statistical data of weather conditions.
(2) Forecast of rail temperature up to about one day later using weather forecast data.

References

[1] Numata, M., “Buckling Strength of Long Welded Rail,” RAILWAY TECHNICAL RESEARCH Report, No.721, 1970 (in Japanese).

[2] Yoshihiko Sato, Satoru Kobayashi, “Numerical Calculation and Approximated Formula of Buckling Strength of Track,” Quarterly Report of RTRI, Vol. 13, No. 1, pp. 35-39, 1972.

[3] Toru Miyai, H., “Numerical Analysis of Track Buckling by Energy Method,” Quarterly Report of RTRI, Vol. 26, No. 3, pp. 81-84, 1985.

[4] Nishinomiya, Y. and Kataoka, H., “Study of the Stability of Continuous Welded Rail in Consideration of a Critical Buckling Temperature Increase,” Journal of Railway Engineering, JSCE, Vol. 20, pp. 9-15 (in Japanese).

[5] Asanuma, K., Tomita, K. and Sogabe, M., “Study on Buckling Temperature of Ballasted Track by Elasto-Plastic and Finite Displacement Analysis,” Journal of JSCE, Ser. A2, Applied Mechanics, Vol. 68, No. 1, pp. 78-91, 2012 (in Japanese).

[6] Saida, A, Fujimoto, A. and Fukihara, T., “Forecasting Model of Road Surface Temperature Along a Road Network by Heat Balance Method,” Journal of JSCE, Ser. E1, Pavement Engineering, Vol. 69, No. 1, pp. 1-11, 2013 (in Japanese).

[7] Zhang, Y., Clemenz, J., Kesler, K. and Lee, S., “Real Time Prediction of Rail Temperature,” AREMA 2007 Annual Conference, Chicago, IL.

[8] Wang, H., Chen, J., Balaguru, P. N. and Al-Nazer, L., “Thermal Benefits of Low Solar Absorption Coating for Preventing Rail Buckling,” Proceedings of the 2015 Joint Rail Conference, March 23-26, 2015, San Jose, CA, USA.

[9] Urakawa, F., “Prediction model of the Rail Temperature in consideration of the Solar Radiation,” 24th Jointed railway technology symposium J-RAIL 2017, Niigata, Japan, S7-6-4, 2017 (in Japanese).

[10] Urakawa, F. and Shigekatsu, K., “Effect evaluation of laying direction on rail temperature using rail temperature prediction model,” JSCE 2018 Annual Meeting, Hokkaido, Japan, VI-859, 2018 (in Japanese).

[11] Hagi, S., Netsudentatu no Kiso to Ensyu (Basics and Exercises of Heat Transfer), Tokai University Press, Kanagawa, Japan, pp. 51-52, 1975 (in Japanese).

Authors

Fumihiro URAKAWA
Assistant Senior Researcher, Track Dynamics Laboratory, Railway Dynamics Division Research Areas: Rail Temperature and Axial Force, Track Buckling, Track Vibration

Shigekatsu KIMURA
Assistant Senior Researcher, Track Dynamics Laboratory, Railway Dynamics Division (Former) Research Areas: Track Maintenance, Railway Tribology

Tsutomu WATANABE, Dr. Eng.
Senior Researcher, Track Dynamics Laboratory, Railway Dynamics Division Research Areas: Dynamic Interaction of Vehicle, Track and Bridge, Vibration Analysis

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