Method for Estimating Snow Accretion on Shinkansen Bogies using Weather Data

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Shinkansen trains operating in snowy areas accumulate snow on their bogies, which can sometimes lead to damage to ground facilities. To prevent this type of damage, snow is removed from trains in stations. We developed a method to estimate the amount of snow accretion on bogies: first, snow density on the railway track is estimated using weather data, then, flying up snow flux is estimated. This is then used to predict the accumulated snow amount under the bogies. Our research confirmed that snow accretion under a bogie upon arrival at a station can be estimated to within 3 cm.

Key words: Shinkansen, bogie, snow accretion, amount of flying snow, estimation of snow accretion

1. Introduction

When railway vehicles run on tracks covered with snow, snow particles fly up and adhere to underfloor equipment and bogies, resulting in a buildup of snow. If this accumulated snow falls when the train is running, it can cause damage to ground facilities or cause a non-changeover event at a point [1]. On conventional lines in Hokkaido, the relationship between weather conditions and snow accretion on bogies has been researched [2], whilst other studies have explored ways to reduce snow accretion on bogies [3]. Other research has been carried out to investigate ways to reduce snow flying up under Shinkansen trains by water sprinkling, in the Tokaido Shinkansen Sekigahara area [4, 5]. Also, some studies have examined methods to prevent snow accretion on vehicle underfloor equipment by mounting underfloor equipment into the body of the train [6]. However, no fundamental countermeasures have been developed targeting bogie sections specifically, because of their complicated shape. Then, it has been demonstrated that this part of trains accumulates a remarkable amount of snow. To reduce the damage caused by dropping snow from such sections, snow removal operations are performed in stations based on weather forecast information. However, sometimes trains arrive with no snow to remove. Therefore, to ensure snow removal operations efficiently, it is important to predict accurately how much snow may have accumulated.

We have studied a method for estimating snow accretion on bogies when vehicles arrive at a station, from information about weather conditions along the railway route in snowy areas [7]. This Snow Accretion Estimation Method has been applied to vehicles running at speeds of up to 130 km/h. The estimation process includes statistical analysis using local meteorological data; therefore, it is unknown whether this method could be applied to estimate snow accretion on Shinkansen vehicles running at a speed of 260 km/h or whether it can be used for estimations in other areas.

Thus, to extend the field of application of this Snow Accretion Estimation Method to Shinkansen vehicles on other routes, we developed a method to estimate snow accretion on bogie section closing plates (CP) from the weather data by measuring snow accretion in stations, and measuring the amount of flying snow in the case of trains running on a viaduct.

2. Data for analysis

The target trains in this study were Hokkaido Shinkansen up lines between Shin-Aomori and Shin-Hakodate-Hokuto Stations (Fig. 1). On these lines, when the snow accretion is expected to increase, snow removal operations are carried out.

Fig. 1 Hokkaido Shinkansen running route and weather observation points of Japan Meteorological Agency

2.1 Snow accretion on vehicle bogie sections

2.1.1 Filming and interpretation methods

A high-speed camera was installed under the up line platform of Shin-Aomori Station to record snow accretion on each vehicle as it entered the station in winter. From this video, stills were extracted for each bogie with the CP positioned in the center of the image. We measured snow accretion on each bogie section CP (Fig. 2) from the stills.

2.1.2 Analysis method

Trains were filmed from 7 December 2017 to 28 February 2018. Total 1083 trains were categorized by the railway operator based on the level of snow accretion on arrival at Shin-Aomori Station. Each bogie section CP at the rear in the train running direction was numbered in order from Car No.1 to 10 (Fig. 3). The snow ac-
cretion on each CP No. during the observation period was averaged for each category ("CP average"). In addition, the level of snow accretion on all CPs on the train were averaged for each train ("Train average").

2.1.3 Result of snow accretion amount analysis

Figure 4 shows an example of the distribution of the CP average for snow accretion categories “Medium” and “Low”. A large amount of snow was found on CP Nos.1 to 3. Then, from CP No.5 onwards, it was revealed a repeated pattern of odd numbered CPs (front bogies on each car) with large amounts of accumulated snow, and even numbered (back bogies on each car) CPs with less accumulated snow.

Figure 5 compares the Train averages with snow accretion averages of CP Nos. 1 to 3. The CP Nos. 1 to 3 average correlates with the Train average. It was found that the largest amount of snow accretion was on the front part of the vehicle; however, even if the train average was approx. 100 mm, CP Nos. 1 to 3 average was sometimes 0 mm. Therefore, if CP Nos. 1 to 3 average is used for analysis, the total snow accretion may be underestimated. Thus, assuming that snow accretion on the entire train set is determined by the weather conditions during operation, we used the Train average to develop the snow accretion estimation method in this study.

2.2 Snow accretion on vehicle bogie sections

We installed observation equipment on a viaduct (Hidariseki; around 9.8 km far from Shin-Aomori station) (Fig. 1). Weather data was collected in the winter of FY2017 (Dec to Feb). In addition, two weather points (Aomori and Kanita) of Japan Meteorological Agency (JMA) were used to estimate snow accretion using the developed estimation method. The weather elements were air temperature, precipitation, amount of solar radiation (calculated from daylight time).

2.3 Snow accretion on vehicle bogie sections

Flying snow flux (kg/m²/s) when trains are running affects snow accretion. Flying snow flux was measured in the winter of FY2017 (Dec to Feb) by using a snow particle counter (SPC: SPC-S7 made by Niigata Electric Co., Ltd). It was installed along the up line maintenance walkway on the viaduct (Hidariseki) (Fig. 6). The SPC is a measuring instrument that counts the number of particles and their size by projecting a slit-type laser (area: 2×25 mm). The volume of a particle is calculated from the measured particle diameter. And then it is multiplied by the density of the ice to calculate the mass. Flying snow flux was calculated from the mass, area, and measuring time. Measurements were taken at 30 kHz for 30 seconds when each train passed. Flying snow flux also depends on train speed [7]. The speed of the train at the observation point was 260 km/h. We used the average value measured for 30 seconds for the analysis when the train passed.
3. Snow Accretion Process and Estimation Method

3.1 Snow accretion process

Snow accretion is considered to occur according to the following process:
I. Snow falls on the track.
II. Trains run over the snow-covered track.
III. Snow flies up as trains run (generation of flying snow).
IV. Snow accumulates on bogie sections.

The Snow Accretion Estimation method reflects these processes and is estimated as follows: (1) weather data used to estimate snow density on the track, (2) snow density and running speed used to estimate flying snow, and (3) estimated flying snow used to estimate snow accretion on the bogie section (Fig. 7).

3.2 Estimating snow density

3.2.1 Snow density and snow flying up mechanism

There are two possible mechanisms underlying snow flying up caused by trains: (1) wind shear forces generated by the running train move snow particles [8] and (2) the pressure difference between the snow surface and the inside snowpack caused by the rapid drop in air pressure when the train passes, causes air movement inside the snowpack, resulting in the scattering of snow particles [9, 10]. In either mechanism, the amount of flying snow may be large when the binding force between snow particles is weak like new snow. After time has passed, the snow density on the surface layer increases due to sintering, consolidation [11], etc., and the binding force also increases between snow particles, and then the amount of flying snow is expected to decrease. Thus, we focus on the snow density which affects snow flying up amount.

3.2.2 Surface Snow Density Estimation Model

After snowfall, surface snow melting occurs under the effect of solar radiation and air temperature. The surface snow layer therefore shrinks and increases in density. We studied this process using a snow cover composition diagram and developed a Surface Snow Density Estimation Model [12]. In this model, the following are assumed.

- Unit volume $V = 1 \text{ m}^3$ and Unit area $S = 1 \text{ m}^2$.
- Surface snow temperature is $0 \degree C$.
- There is neither loss of water due to evaporation nor infiltration into the lower layer.
- Snow is dry just after snowfall.
- Consolidation of surface layer, mass of air in the snow cover, volume change during water-ice phase change can be ignored.

Snow density before snow melting is $\rho_s$ and the density after snow melting is $\rho_{s1}$, the density increase due to snow melting is expressed by (1) (Fig. 8).

$$\rho_{s1} = \frac{\rho_s}{1 - \frac{m_i}{m_{\text{M}}}}$$

where $m_i$ is the mass (kg) of ice, and the snow melting mass, $m_{\text{M}}$ (kg), is converted from the surface snow melting amount $M$ (mm), using (2).

$$m_{\text{M}} = M \times 10^{-3} \times S \times \rho_w$$

where $\rho_w$ is the density of water (1000 kg/m$^3$).

The surface snowmelt amount $M$ can be obtained by the heat balance method, but many meteorological factors such as the net radiation are required for the calculation. However, considering the introduction to practice in the railway field, a few meteorological factors at short time intervals are required. We used the snow melting model (3), proposed by Konya et al. [13], which can calculate the surface snowmelt amount $M$ every hour.

$$M = aK_d + bT_a + c$$

where $K_d$ is the amount of solar radiation (W/m$^2$), and $T_a$ is the air temperature ($\degree C$). Coefficients $a$, $b$, and $c$ are determined by the multiple regression analysis with the observation data.

Initial snow density is given in the air temperature range of $-10$ to $1 \degree C$ by using (4). This is an empirical equation obtained from the result of measuring the snowfall density for a short time [14].

$$\rho_{s0} = 53.6 \exp(0.488T_a) + 37.0$$

where $\rho_{s0}$ is the snowfall density (kg/m$^3$), and $T_a$ is the air temperature ($\degree C$).
The change in snow density on the snow cover surface layer is repeatedly calculated every hour beginning immediately after the snowfall until the next snowfall.

3.2.3 Determination of melting coefficients

To use the Surface Snow Density Estimation Model, we need to obtain the surface snowmelt amount $M$. Coefficients $a$, $b$, and $c$ of (3) were determined by comparing measured snow density at Hidariseki. The estimated density agreed with measured snow densities by setting the coefficients as $a = 0.018$, $b = 1$, and $c = -0.5$ (Fig. 9).

3.3 Estimating the amount of flying snow

Temperature, precipitation, and solar radiation measured on the viaduct were input to the Surface Snow Density Estimation Model, and the snow density on the track was estimated. The relationship between flying snow flux for passing trains and the estimated snow density was examined (Fig. 10). As the data included a variation, the regression curve shows that the flying snow flux was large where the estimated snow density was approx. 50 kg/m$^3$, but it decreased when the estimated snow density increased. If density exceeds 150 kg/m$^3$, the flux falls to approx. 0 kg/m$^2$/s. This is because as the density of surface layer increases, it is difficult for the snow to fly up as described in Section 3.2. The relational expression between the estimated snow density and flying snow flux (correlation coefficient $R = 0.71$) is (5):

$$F = 0.97 - 5.08 \times 10^4 \rho_s - 5.61 \times 10^5 \rho_s^2 - 5.75 \times 10^6 \rho_s^3 + 9.27 \times 10^7 \rho_s^4 - 4.36 \times 10^8 \rho_s^5 + 6.67 \times 10^9 \rho_s^6$$

where $F$ is the flying snow flux (kg/m$^2$/s), and $\rho_s$ is the estimated snow density (kg/m$^3$).

It is reported that even at the same snow density, the higher the running speed, the greater the amount of flying snow [7]. Since trains are slow down near stations, the flying snow flux is also assumed to diminish. In this study, equation (5) was used because of the safer evaluation.

3.4 Relationship between amount of flying snow and snow accretion

Railway operators provided the following information: accumulated snow disappeared from the target trains when they were running through the Seikan Tunnel and there was almost no snow accretion on trains at the Tsugaru Yomogita Tunnel entrance. This allows us to assume that snow accumulated in the open section of approx. 18.7 km between the Tsugaru Yomogita Tunnel entrance to Shin-Aomori Station. The speed of snow accretion was calculated by dividing the Train average at Shin-Aomori Station by the running time of 410 sec. in the open section. Figure 11 shows the relationship between the flying snow flux on the Hidariseki viaduct and the speed of snow accretion.

The speed of snow accretion tends to increase as the flying snow flux increases, although it includes a variation. The following can be listed as possible causes of the variation:

1. The amount of snow accumulated on the CP is considered to reflect the flying snow flux along the wayside; however, the flying snow flux at the observation point on the viaduct may differ from that observed at other points.
2. The train average may be affected by dropping snow from the target train.

The relationship between the flying snow flux and the speed of snow accretion is expressed by the following regression equation (6).

$$V_L = a \times F^b$$

where $V_L$ is the speed of snow accretion (mm/s), and $F$ is the flying snow flux (kg/m$^2$/s).

Fig. 8 Density change in the composition diagram

Fig. 9 Comparison between the estimated and measured snow densities

Fig. 10 Estimated snow density vs. flying snow flux

Fig. 11 Flying snow flux vs. snow accretion speed
There is the problem that the measured data is not always a representative value because it is a value of one point. Therefore, we set coefficients $a$ and $b$ of (6) so that the estimated value by the Snow Accretion Amount Estimation Method does not fall below the maximum value of the measured snow accretion at Shin-Aomori Station.

4. Verifying Snow Accretion Estimation Method

Figure 12 show the method used for calculating snow accretion at a certain point from weather data, assuming a vehicle running from Point I to II:

1. Set the assigned sections according to the meteorological observation points and the obtained weather data.
2. Calculate the snow accretion in each section by using the Snow Accretion Estimation Method.
3. Accumulate the snow accretion in each section to estimate snow accretion at Point II.

This calculation assumes that the accumulated snow does not melt or drop as the train runs and that the snow accretion increases monotonically.

The estimated snow accretion extension amount upon arrival at Shin-Aomori Station was obtained using weather data from Aomori and Kanita of JMA. Coefficients $a = 7.5$ and $b = 0.9$ were used for the relational expression (6).

Figure 13 shows a comparison between the measured and estimated snow accretion values upon arrival at Shin-Aomori Station. There is a positive correlation between estimated values and measured values, although estimated value often exceeded measured values. The maximum difference between the measured and estimated values was 171 mm, however, the root mean square error (RMSE) was 28.5 mm. Therefore, it was confirmed that the estimation error by this estimation method was approx. 3 cm.

5. Conclusions

In order to develop the Snow Accretion Estimation Method, we measured snow accretion on bogie sections on trains arriving in a station and the amount of flying snow on a viaduct. We developed a method to estimate the amount of snow accretion on bogies: first, snow density on the railway track is estimated using weather data, then, flying snow flux is estimated. This is then used to predict the accumulated snow amount under the bogies.

We estimated snow accretion on the bogie section closing plates of Shinkansen vehicles arriving at Shin-Aomori Station and compared with measured values. It was confirmed that developed method can estimate snow accretion within an error of approx. 3 cm.

We hope that the results obtained in this study will contribute to developing effective measures against snow dropping troubles.

Acknowledgment

The authors would like to express our deepest gratitude to all concerned parties of Hokkaido Railway Company and East Japan Railway Company for their great cooperation in acquiring the data.

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