Method of Calculating Running Resistance by the Use of the Train Data Collection Device

Tomoyuki OGAWA
Hydrogen and Sustainable Energy Systems Laboratory, Vehicle Control Technology Division

Shinichi MANABE
Drive Systems Laboratory, Vehicle Control Technology Division (Former)

Gaku YOSHIKAWA
Traction Control Laboratory, Vehicle Control Technology Division

Yoichi IMAMURA
Masahisa KAGEYAMA
West Japan Railway Company

Running resistance is one of the important factors in the design of train performance and the planning of speed profiles. Running resistance is also an important factor in the analysis of energy consumption, because it is the main source of energy consumption. This paper proposes a method for calculating running resistance under various conditions by using commercial running data obtained through a train data collection device instead of running tests. This paper describes how the proposed method was verified through running tests, and presents running resistance under various conditions calculated using the proposed method.

Keywords: running resistance, train data collection device, energy consumption, energy calculation, mechanical resistance, pneumatic resistance

1. Introduction

Running resistance is one of the most important factors in train performance design and planning of speed profiles. Running resistance is also important for analyzing energy consumption, because it is the main source of energy consumption. Figure 1 shows an example of the breakdown of energy consumption calculated by a train running energy simulator [1]. Energy losses from running resistance account for 37 % of local train energy consumption and 52 % of rapid energy consumption train running on the same section of a line. This illustrates how important running resistance is for saving energy. However, the quantitative calculation of running resistance is done under limited conditions, because the running resistance depends not only on the type of train and running speed, but also other factors, such as the existence and the shape of tunnel structures, the type of tracks, and passenger mass.

Running resistance is obtained through running tests. A coasting method is generally applied to the calculation of the running resistance. In the coasting method, the running resistance is calculated by deceleration while coasting. For example, to obtain the measurement, running tests are conducted about 10 times. The running resistance for each train speed is calculated from the deceleration in each measurement obtained from the coasting runs. The equation for running resistance is then obtained through approximation of these results. In sum, measuring running resistance through running tests is time consuming. A method has therefore been developed for calculating running resistance by using commercial running data obtained from a train data collection device.

Compared to data collected through running tests, large volumes of data can obtained from commercial running data, because they are produced daily. However, commercial running data is not collected under controlled conditions, like in tests, and does not necessarily correspond to analyses conditions because the trains are operating according to train schedules. Moreover, while measurement staff obtains various conditions not recorded on the measurement data at the running test, the commercial running data only provides data which is recorded. In other words, reliability of the commercial running data is lower than running test data. The proposed method aims to overcome this problem through volume of data.

The developed method makes it possible to obtain run-
ning resistance without conducting running tests and for a wide range of conditions, such as for different types of tunnel structure, track, and passenger mass.

2. Outline of the train data collection device

2.1 An EMU

The DC commuter EMU (Electric Multiple Unit) used for the analysis consisted of 7 cars and was equipped with a digital transmission device. Control data and monitor data are shared by the digital transmission device. The train data collection device collected commercial running data through the digital transmission device. Table 1 shows the features of the EMU used for the analysis.

| Table 1 Features of the EMU used for the analysis |
|-----------------------------------------------|
| Train set | 6 motor cars and 1 trailer car (6 motor bogies and 8 trailer bogies) |
| Train mass | 232.8 [t] |
| Inertia ratio | Motor car: 1.08, Trailer car: 1.06 |
| Bogie | Bolsterless bogie, Beam type axle box suspension |
| Maximum speed | 120 [km/h] |
| Wheel diameter | 860 [mm] (new) |
| Bearing for axle | Tapered roller bearing |
| Length of car | 20000 [mm] |
| Width of car | 2950 [mm] |
| Height of car | 3630 [mm] |

2.2 Transmission of the train data collection device

Figure 2 shows the outline of the train data collection device. The train data collection device transmitted the commercial running data to a server computer in an office using a wayside wireless WAN (Wide Area Network).

2.3 Data for the analysis

Data for the analysis is the commercial running data obtained from December 2009 to August 2014 for two train sets. A Comma Separated Values (CSV) file is generated for each stop station. About 420,000 files were recorded for the analysis, totaling approximately 900 GB. About 250 items were recorded including time, position, speed, notch, voltage, current, brake force, pressure of air suspension, flag of slip, flag of slide, and so on, for each car, unit or axle; with a recording interval of 0.08 [s]. Speed was recorded by a figure with the first and second decimal places and it is calculated from the speed of each axle with averaging and decimation.

2.4 Acceleration analysis system

Systems were developed to analyze large volumes of data, one of which was the acceleration analysis system. The acceleration analysis system calculates acceleration from commercial running data with filter processing. Since acceleration analysis needs to take route profile into account, it corresponds to the track and structure database, which can provide the route profile of each position. The acceleration analysis system can therefore be used to analyze traction performance, running resistance, and braking performance.

3. Running resistance calculation method

3.1 Coasting method

While coasting, running resistance \( R_c \) [kN] is calculated by deceleration \( \beta \) [km/h/s], equivalent train set mass \( M \) [t], gradient resistance \( R_g \) [kN], and curve resistance \( R_c \) [kN], as shown in (1). The equivalent train set mass means the sum of train set mass, inertial mass, and passenger mass.

\[
R_c + R_g + R_s = \frac{1000}{3600} M \beta
\]

(1)

Thus, running resistance is calculated by the deceleration, the gradient resistance, and the curve resistance.

The gradient resistance is calculated by the gradient of the running position \( S \) [%] and the gravity acceleration \( \beta \) [m/s/s], as shown in (2).

\[
R_g = \frac{1}{1000} S M g
\]

(2)

The curve resistance is calculated by the radius of the curve of the running position \( C \) [m] and the coefficient \( K \), as shown in (3).

\[
R_c = \frac{1}{1000} K M g \]

(3)
3.2 Calculation through measurement

In the measurement method, the train coasts through each test position. The running resistance is then calculated from deceleration at each test position. The equation of the running resistance is derived by a quadratic polynomial expression as an approximation equation using the least-square method from a figure with speed on the horizontal axis and running resistance on the vertical axis. Figure 3 shows the running resistance through measurement. Each plot shows the deceleration of each test position sampled at intervals of 0.5 [s]. Number of plots is 3032. The gradient resistance is calculated by (2) using the gradient of the test position and a curve resistance of zero, because the test position is selected from among straight sections of a line with no variation in gradient.

3.3 Running data analysis calculation method

3.3.1 Outline of the calculation method

Figure 4 shows the running data analysis method for calculating running resistance. Figure 5 shows the extraction method. In the running data analysis method, deceleration is calculated from change in speed in commercial...
running data obtained as time-series data. The gradient of the running position is obtained from the track and structure database using a running position estimation method based on commercial running data. The gradient resistance is calculated with the gradient from the running position.

Through this method, analysis is limited to data obtained when the whole train set is in a section where the gradient is constant. The analysis does not include areas in the vicinity of the point where the gradient changes, because gradients vary through transition, which means that estimation errors would be inevitable in the running position estimation method being used.

The analysis in this method does not include curved sections, because (3) is a low-accuracy simplified equation. In addition, similar to the gradient resistance, this analysis does not include areas each side of a curve, given the variation in radius in the transition sections, which would cause inevitable errors in estimation.

Given that running resistance depends on the existence of tunnels and their structure, the type of tracks and passenger mass, calculation results are categorized according to the information relating to these factors. Track and structure data is obtained from the track and structure database, and passenger mass information is obtained from the commercial running data.

### 3.3.2 Running position estimation method

The running position estimation method is based on train speed and the running section recorded through the commercial running data. At time $T_i$, the head position of the train $L_{h_i}$ [m] is calculated by the position of the stop sign at a departure station $L_{s_i}$ [m] on the track and structure database using (4).

$$L_{h_i} = L_{s_i} + \frac{1000}{3600} \int_{T_{i}}^{T_{i+1}} v(t)dt$$  \hspace{1cm} (4)

At time $T_{i+1}$, when the train arrives in a station, the head position of the train $L_{h_i}$ [m] is expected to be equal to the position of the stop sign in that station $L_{s_i}$ [m] which is obtained as a result of the calculation by (5). However, this method includes errors of the integration of speed and differences between managed positions and actual positions. Furthermore, commercial running data may be insufficient due to information transmission errors. Thus, sections with data exceeding the error thresholds are excluded from the analysis.

$$L_{h_i} = L_{s_i} + \frac{1000}{3600} \int_{T_{i}}^{T_{i+1}} v(t)dt$$  \hspace{1cm} (5)

### 3.3.3 Method for calculating deceleration

This section shows the method for calculating deceleration from discrete commercial running data. For recorded number of $i$ at time $T_i$ [s], deceleration $\beta$ [i] [km/h/s] is calculated by the train speed $v[i]$ [km/h] and the interval of recording $\Delta T$ [s], as shown in (6).

$$\beta[i] = \frac{v[i-1] - v[i+1]}{2\Delta T}$$  \hspace{1cm} (6)

Because the running resistance is calculated from train speed, the accuracy of the running resistance depends on the accuracy of the train speed. The train speed is detected by a speed sensor mounted on the axle end. The speed sensor of the train for this analysis was a non-contact induction generator. Square waves are generated according to the rotation of the axle. Because of the count error of square waves and mechanical vibrations which generate errors in train speed detected, there is a limit to train speed accuracy.

The train for the analysis had recording intervals of 0.08 [s]. The speed data had short-time vibrations. Under this method, momentary vibrations were removed because this method was aimed at obtaining running resistance tendencies for a wide speed range. Thus, under this method two-step removal was employed. In the first step, instantaneous deceleration $\beta[i]$ [km/h/s] was calculated by the train speed $v[i]$ [km/h] using backward and forward time $T_i$ [s], as shown in (7). In the second step, averaged deceleration $\beta_a[i]$ [km/h/s] at record $i$ was calculated by the instantaneous deceleration $\beta[i]$ [km/h/s] using backward and forward record $N$, as shown in (8). Moreover, in terms of the removal of momentary vibrations, it was preferable when $N$ was large. However, the range of the data extracted, provided that notch, gradient, and curve were constant in the section where data was extracted, was limited when $N$ was large. In this report, 4 is selected as $N$. Equation (9) is obtained by (7) and (8).

$$\beta[i] = v[i] - v[i+\frac{T_i}{\Delta T}]$$  \hspace{1cm} (7)

$$\beta_a[i] = \frac{1}{2N+1} \sum_{n=-N}^{N} \beta[i+n]$$  \hspace{1cm} (8)

$$\beta_a[i] = \frac{1}{2N+1} \sum_{n=-N}^{N} v[i - \frac{T_i}{\Delta T} + n] - v[i + \frac{T_i}{\Delta T} + n]$$  \hspace{1cm} (9)

### 3.3.4 Extraction

The coasting method requires a judgment of coasting. In the commercial running data, acceleration notches and braking notches are recorded. The record of a state in which these notches are not used means coasting. However, jerk controls delay actual acceleration after the use of these notches. In this method, the analysis excludes the data in the vicinity of notch changes.

Slips and slides also cause speed errors. In the coasting method, extracted data excluded slips in powering and slides in braking. However, slips and slides can generate errors in the running position estimation method when obtained through equation (4). Since the trains used for the analysis had many trailer axles, slips due to powering were considered to only rarely influence train speed calculations. On the other hand, sliding during braking however, remained an influence. This method therefore concentrates the analysis to data with few slipping or sliding flags.
3.3.5 Sampling

Under the running data analysis method, more plots were obtained than through measurement. Test points with a specified train speed however, could not be set. The number of samples differed depending on train speed. To reduce the difference, sampling based on the train speed was introduced instead of time interval sampling used in the measurement. Accordingly, the data were sampled at train speed intervals of $\Delta V$ [km/h] as shown in Fig. 6. In this report, the speed interval $\Delta V$ [km/h] is 2.0 [km/h].

4. Analyses results

4.1 Result of the running data analysis method

Figure 7 shows the running resistance calculated with the running data analysis method. Table 2 shows the extraction conditions. In order to compare this method with measurements, this figure shows data extracted under the same conditions as those applied for the measurements. There are 11859 plots. Figure 8 shows the histogram of the train speed. Because the data are extracted from the coasting data of the commercial running data in this method, the number of data at high speed is large and that at low speed is small.

4.2 Verification of the analysis method

Figure 9 shows the comparison between the measurement and the running data analysis method. This figure also shows the running resistance of the Japanese Industrial Standards (the JIS equation), which is widely used. Because the JIS equation was established many years ago, it is no longer deemed suited to modern trains. The running resistances obtained through measurements and the running data analysis method are in good agreement. Figure 10 shows the result of energy calculations for each running resistance, obtained from the train running energy simulator. In the energy calculation, the difference in running resistance leads to a difference in running time. The simulation employs the function of a speed profile generator for an energy estimation [2], which adjusts the speed profile to a given running time. As a result, energy consumption calculated with the running data analysis method is 0.1 % higher than that obtained through measurement. This confirmed that the running data analysis method was equivalent to measurements.
4.3 Comparison with tunnel sections

The running data analysis method also enables us to calculate running resistance under various conditions not obtained from measurements. Running resistance at high speed is greatly influenced by pneumatic resistance in tunnels. Figure 11 compares running resistance in a tunnel section and an open air section obtained through the running data analysis method. Table 3 shows the extraction conditions. The underground tunnel results show are for a single-track tunnel in a city. The mountain tunnel results are of a double-track tunnel. This method enables us to obtain the running resistance quantitatively according to the cross-sectional shape of the tunnel. Therefore, under this method, the intercept of the running resistance in the open air was used. The limited speed range is an issue for this method, however it can be used to estimate the running resistance at high speed. The majority of commercial runs are high speed. The running resistance at high speed is greatly influenced by tunnel sections. It is thought that the running data analysis is an effective method for estimating running resistance.

5. Conclusions

A method has been proposed for calculating running resistance under various conditions by using commercial running data obtained from train data collection devices, instead of through running tests. Running resistances obtained from running test measurements and from the running data analysis method are in good agreement. Verifications confirmed that the proposed method is sufficiently accurate for practical application, as energy calculations suggest. The proposed method was then used to calculate running resistance under other various running conditions.

Issues relating to the running data analysis method are that speed range data is limited and accumulating commercial running data takes time. Other important factors influencing this method are: accuracy and time intervals of the speed data collected through the train data collection devices; as are accuracy of gradient, curve, points, and stop sign positions on the track in the track and structure database.

In future, more widespread use of train data collection devices will make it possible to conduct more running resistance analyses. These analyses will allow further quantitative running resistance examinations to be conducted under more precise conditions.

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Authors

Tomoyuki OGAWA, Dr. Eng.
Assistant Senior Researcher, Hydrogen and Sustainable Energy Systems Laboratory, Vehicle Control Technology Division
Research Areas: Energy Simulation, Analysis of Train Information

Shinichi MANABE
Researcher, Drive Systems Laboratory, Vehicle Control Technology Division (Former)
Research Areas: Condition Monitoring, Running Resistance

Gaku YOSHIKAWA, Dr. Eng.
Researcher, Traction Control Laboratory, Vehicle Control Technology Division
Research Areas: Running Resistance

Yoichi IMAMURA
Deputy General Manager, Rolling Stock Dept., Railway Operations Headquarters, West Japan Railway Company
Research Areas: Vehicle technology & Vehicle development

Masahisa KAGEYAMA
Senior Engineer of Technical Research & Development Dept. Railway Operations Headquarters, West Japan Railway Company
Research Areas: Vehicle technology