An Evaluation Method of the Braking Performance Using Bogie Traction Force

Shin-ichi SAGA

Brake Control Laboratory, Vehicle Control Technology Division

Minoru MIYABE

Junya KAWAMURA

Hironobu SUGITA

Katsutoshi CHIKUMA

West Japan Railway Company

The adhesion coefficient between rail and wheel of the railway vehicle is reduced under rainy weather, so it is difficult to obtain high braking performance. In general, the braking performance of the train is evaluated to be based on the stopping distances and the deceleration which is obtained by calculating the rotational velocity of the wheel. However, braking performance degradation is caused by the complex combination of the bad condition of the adhesion coefficient between rail and wheel, the friction coefficient of composite braking materials and the wheel slip control. In order to investigate the factor of the degradation of the braking performance in the high speed train or the shortening of the braking distance, it is desired to measure the variation of the braking force at each bogie. We have developed an evaluation method of measuring the braking force of the actual vehicle with the force acting on the single-link type traction device. In this paper, the results of a running test by means of this evaluation method of the braking performance using bogie traction force are reported.

Keywords: traction force, single-link type traction device, braking performance, adhesion, slip

1. Introduction

Braking performance of train set is generally evaluated based on the distance required for stopping and the deceleration that are calculated from the wheel-rotation velocity. It may however sometimes make it difficult under wet conditions such as in rains to identify its origins for the performance deterioration only from the velocity because other factors such as friction coefficients of braking materials and re-adhesive sliding control are complicatedly affect it as well as the degradation of adhesive coefficients between rail and wheel.

In such cases, it is quantitatively envisaged to see how adhesion coefficients between rail and wheel and other factors may affect such phenomena if the braking force specified for each axle or bogie (tangential force between rail and wheel) can be directly measured while vehicle is running.

However, the conventional process having been used for measuring braking forces for each axle, requiring quite a large amount of time and effort for modeling and calibration, was limited in application ranges for actual trains. Considering the further speedup expected in the near future, higher braking force against earthquakes, short train-set, on the other hand, a more accurate evaluative method for braking performance is required. A higher-precision technique for measuring the braking force for each bogie is offered here that precisely examine it in response to the force acting on the single-link type traction device (a bogie-traction device), and its effectiveness has also been verified through actual running tests on conventional and Shinkansen train.

2. Conventional method for evaluating braking performances

2.1 Measurement process of braking forces

The conventional process starts with preliminarily sticking of a strain gauge on the arm of foundation braking-gear or on the brake-shoe hanger (Fig. 1) at a fixed spot, to obtain its correlation with that appearing on loading a vertical static load on the brake shoe (at the effective braking radius). The braking force (frictional force) is then determined from the result of fixedly stuck gauges by measuring the strain while braking operation on the running test. The adhesion coefficient was further determined using this traditional procedure from the initial braking force on slipping by forcing it to brake only the axle subject to study during coasting by a train-set operation. The advantage of this process is the capability for capturing one-wheel or one-axle braking force.

Meanwhile, there are also weak points such as the requirement for preliminary calibration by dismantling the foundation braking device from the bogie, large amount of gauge working disabling easy process management within the test period, limitation to the measurement during air-braking, running vibration or pressure components randomly appearing as external disturbances, and incapability for handling continuous phenomena including train-set braking and re-adhesion control on sliding.

From these aspects, there are not enough R&D reports available on adhesion characteristics for actual vehicles and train-sets [1].

Fig. 1 Examples of locations for strain gauges

2.2 Measurement examples of adhesion coefficients

Adhesion coefficient μ between rail and wheel is defined as maximum tangential force on wheel-slipping F_{imax} divided by static wheel weight W (1). While the wheel stands adhesive when the braking force is smaller than the tangential force, it slides vice versa. The adhesion coefficient therefore determines every state of slip, giving the following prospective equations. Prospective adhesion coefficient μ_w under wet conditions is expressed as (2) for velocity V (km/h), also giving its twofold value for dry conditions [2]. The deceleration β (km/h/s) given here can be derived from (3) using gravity acceleration g and adhesion coefficient μ . The value of deceleration for Shinkansen trains legally specified is that for emergency brake, having been regulated as what is stably determined also in wet rail condition.

$$\mu = F_{imax} / W \quad (1)$$

$$\mu_w = 13.6 / (V + 85) \quad (2)$$

$$\beta = 3.6g\mu \quad (3)$$

Figure 2 shows here a result of adhesion coefficients for 200-series Shinkansen trains in wet rail condition [3] obtained by the conventional measurement process of braking forces. Those measured values are distributed in the range between dry and wet prospective adhesion coefficients, showing lower values in head vehicles than in the third car.

Fig. 2 Adhesion coefficient in wet rail (200-series)

3. New evaluation method for braking performances

3.1 Bogie traction force by single-link type traction device

The recent railway vehicle mainly employs air-pressure bolster-less bogies intended for lighter weight. This mechanism transfers driving and braking forces between car body and bogies directly through single-link type traction device with large permissible displacement of air spring. Single-link type traction device, consisting of simple geometries, has an advantage of comparatively easy measurement of forces on acceleration and deceleration.

A new method for measuring braking forces from a traction force exerted on the single-link type traction device has been offered here as a countermeasure to make up for the weak points of the conventional process (Fig. 3). This process, needless to dismantle brakes, has advantageous feature of high-precision examination for braking forces working on each bogie comprising the train-set brakes, as well as with electric and air brakes.

Fig. 3 Location for strain gauges (single-link type traction device)

A 4-active-gauge method (perpendicular placement) has been applied for measuring tensile/compressive loads acting on the main part of the single-link type traction device. It has advantages against 1-gauge method such as deleting bending components, improving the strain sensitivity, and temperature compensation. The theoretical value of axial load P (kN) for a typical single-link type traction device geometry (outer diameter: 70 mm, inner diameter: 40 mm) widely applied for many vehicles will be determined by (4) using a strain s ($\mu\epsilon$).

$$P = 0.205s \quad (4)$$

3.2 Load calibration using regenerative brake

Figure 4 shows an example of actual measurements using this process for B7 braking (maximum in service operation) from 170 km/h (initial velocity) of motor-car of Shinkansen. Braking information transmitted from brake controllers and main converters comprises notch, velocity, BC pressure, pattern voltage of regenerative brakes, regenerative feedback voltage, motor current, command voltage for air-brake subtraction. Among these, regenerative feedback voltage and strain exhibit a similar feature with high correlation. It is therefore reasonable to calibrate the strain by a braking force convertible from the regenerative feedback voltage (electric braking force hereinafter).

Figure 5 shows a result of calibration factors. Bogie

Fig. 4 Measurement example of braking test

Fig. 5 Calculation results of calibration factors

2 (front side in testing direction) takes a negative value (compressive) and Bogie 1 (back side) shows positive (tensile). The strain values actually obtained from an electric brake is lower than the theoretical value given for individual single-link type traction device, showing its calibration factor as 0.3 against 0.205.

It is considered for this cause as having been affected by the spring stiffness such as of couplers, dampers, and air springs. Judging from the results for other vehicles showing 0.2 – 0.35 as calibration factors, about 20 – 40 % of the braking forces is concluded as shared by spring systems other than the single-link type traction device. This also coincides with the fact that the spring stiffness vary with types of bogies (motor-bogie or trailer-bogie with different calibration factors).

3.3 Load calibration using longitudinal deceleration

Braking behaviors of trailer-bogie (trailer-car) will be commented in next. As only air brakes typically act on trailer-bogies with frictional forces fluctuating with the BC pressure specified by an air-brake subtraction command, the same process for motor-bogies (utilizing the proportional relationship with electric braking force) cannot be applied to them. Another proportional characteristic between the strain appearing on the single-link type traction device and the longitudinal deceleration will be used to (Fig. 6). There are however restrictions such as the data subject to calibration limited to the setting of the 100 % brake loading ratio and possibility of calibration precision lower than that of motor-bogie.

The calibration process will be concretely commented

Fig. 6 Relationship between strain and longitudinal deceleration

Fig. 7 Calibration result using each method

below. Setting the calibration factor for both bogies as γ , strains for Bogies 1 and 2 respectively as s_1 ($\mu\epsilon$) and s_2 ($\mu\epsilon$), longitudinal deceleration as β (km/h/s), vehicle mass as M (ton), and inertia coefficient as k (motor-bogie: 1.1, trailer-bogie: 1.05), the calibration factor γ is given by (5). Calculating it from the start to the end of braking operation in each notch condition for sampling lots, the factor γ is determined by averaging the values within a range where the values are stabilized.

$$\gamma = Mk(\beta / 3.6) / (|s_1| + |s_2|) \quad (5)$$

Figure 7 shows a calibration result. The results calibrated by electric brake and longitudinal deceleration well coincide with each other. This procedure is used to extended also to estimate the friction coefficients of shoes and linings of air brakes (averaging it over a bogie).

4. Evaluation examples of braking performance

4.1 Conventional train

This evaluation procedure has been applied to the running test with conventional 3-vehicle train-set (1M2T) as shown in Fig. 8.

Items subject to measurement include notch, axle velocity, BC pressure, pattern voltage of regenerative brake, regenerative feedback voltage, subtraction command voltage for air brake, single-link type traction device strain, longitudinal deceleration, and valve signal for slide preven-

Fig. 8 Experimental train-set (1M2T)

tion. Meanwhile, braking is controlled via air supplement with higher priority on T-series car, and wheel-slide re-adhesive control for each axle.

4.1.1 Braking performance in dry condition

Figure 9 shows a measurement result of 3-notch electric-brakes in service (B3). B3 is a brake setting with regeneration effective by loading the braking force as a train-set on Mc-vehicle. While each vehicle actuates air brakes triggered by a braking command, T-series and Mc-vehicle hold their braking forces suppressive in response to the activation of electric brakes at Mc vehicle. As the train-set braking force in this case satisfies the total force required (100 %), a well-balanced air supplement is observed here.

Later, in reply to the Mc-vehicle degrading the regenerative braking force from 20 km/h, T and Tpc-vehicle supplement their air brakes to actuate the braking force.

Fig. 9 Measurement result in dry (electric brake B3)

4.1.2 Braking performances in wet condition

Figure 10 shows a measurement result of a 3-notch condition with electric brakes in service when the Mc-vehicle slips due to the drop of adhesion coefficient in rains between rail and wheel. The Mc-vehicle transmits an air-brake subtraction command to the T and Tpc-vehicles once it lowers the electric braking force on detecting the slip. In response to this process, the T and Tpc-vehicles start to control the supplement of brake-force shortage at the Mc-vehicle immediately by actuating the air brake. While the braking force as a train-set deteriorates along with the Mc-vehicle starting to slip and its control, repeating increase/decrease against the braking force required, there is no problem against the braking performance because the extension of the braking distance stays within about 10 %.

Another example where the two axles at a trailer bogie

Fig. 10 Measurement result in wet (electric brake B3)

Fig. 11 Estimation of adhesion force while slipping

slide at the same time will be commented in next (Fig. 11). It is observed here that the BC pressure is quickly charged to the proper value after detecting a re-adhesion by exhausting or holding the pressure in each axis through re-adhesive control. Paying attention to the braking force from the sliding convergence until re-adhesion, there is a peak value appearing after the brake force rapidly increases despite the BC pressure not reaching the prospective value while the both axles slide. Ohyama et al. reports that it is an increase of the adhesive force in macro-slip area [4].

The maximum adhesion force F_m (N) is given by (6) for the tangential force on wheel treads as F_b (N), inertia moment of wheels as I (kg/m²), wheel diameter as R_w (m), deceleration as train-set as β (km/h/s), and wheel deceleration as β_w (km/h/s).

$$F_m = F_b - \left\{ \left(I / R_w^2 \right) (-\beta - \beta_w) \right\} \quad (6)$$

It is verified from the chart that the maximum adhesion force estimated here shows a same feature as that of the braking force and that the behavior of the braking force in slips is captured in detail.

4.1.3 Adhesion coefficient and tangential-force coefficient

Another example with a train-set different from the above (1M2T) will be commented below which sprinkles the front and third axles (5 lit. per wheel for every minute) to artificially cause a large slip. The adhesion coefficients in

Fig. 12 Adhesion coefficient measurement result

Fig. 13 Measurement result between slip rate and tangential force coefficient

Fig. 12 were obtained by assuming that the braking force is regarded as evenly shared until an instant when an axle on one side in the bogie starts to slide, which shows measurement results along the prospective equations in wet conditions. Figure 13, determining a relationship between the slip rate (averaging the values over the bogie while sliding) and the tangential-force coefficients, on the other hand, shows a drop in tangential-force coefficient along with the increase of slip rate. This feature is particularly obvious for Bogie 2 (with maximum slip rate reaching 30 %) as previously reported, thereby proving the high applicability of this process.

4.2 Shinkansen train

This procedure has been applied to the running test using a Shinkansen train with 8 vehicles (8M) (Fig. 14). Cars subject to test were 4 vehicles from the head (Car 1 – 4). Items subject to measurement are notch, axle velocity, BC pressure, pattern voltage of regenerative brake, regenerative feedback voltage, single-link type traction device strain, longitudinal deceleration, and valve signal for slip prevention. Sliding re-adhesion is controlled for each axle at Car 1 and for bogies at Car 2 – 4.

Emergency electric brakes (EB) were chosen for braking from 300 km/h (initial velocity) to 120 km/h. The emergency brake is configured so as to jet alumina particles for adhesive promotion for 1 minute from the ceramic injector that is mounted on the head axle. The second and sixth

Fig. 14 Experimental train-unit (8M)

Fig. 15 Measurement result of tangential force coefficient over each car (dry with ceramic injection)

Fig. 16 Measurement result of tangential force coefficient over each car (wet without ceramic injection)

Fig. 17 Measurement result of tangential force coefficient over each car (wet with ceramic injection)

axles are equipped with sprinkler nozzles, which jet 5.5 lit. per wheel for every minute.

The braking performance was evaluated by comparing the tangential-force coefficients (obtained by calculation from the braking forces) with the prospective values of adhesion coefficients.

Any test car shows satisfactory adhesion coefficients required for emergency brakes (equal to EB) in the current condition (with ceramic injection in dry conditions) (Fig. 15). Continuous slips were observed at Car 1 and 2 in wet conditions without ceramic injection, which may degrade the adhesions to the level of prospective values (Fig. 16). While such tendency may be affected by sliding re-adhesive control as well as low adhesion conditions between rail and wheel, the extension of braking distance as a train-set is kept within about 2 %, thereby giving no problem to the braking performances.

In wet conditions with ceramic injection, it is observed that the slip occurrence is suppressed with the recovery of tangential force coefficient (Fig. 17). The reason why the tangential force coefficient is still low at Car 2 is considered affected by the large water amount reaching the wheels at Car 2 judging from the watering positions.

5. Conclusion

From the running tests using actual train, an effectiveness of the evaluation method for braking performances with traction force has been verified here. This method is capable for measurement and evaluation of braking forces

with high precision regardless of brake types (electric or air) while mitigating the preparatory works required for measurement.

Furthermore, it may contribute to the proper analyzing of the complicated phenomena and performance on braking influenced by velocities, rail environments, and control characteristics without applying conventional operations having been required for each axle, and also further to the adaptation of brake loading ratio design.

It will be further optimized for higher precision in rains and snows from now on by accumulating the data for braking forces.

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Authors

Shinichi SAGA
Senior Researcher, Brake Control Laboratory,
Vehicle Control Technology Division
Research Areas: Brake System

Hironobu SUGITA
Researcher, High Speed Vehicle Section,
Technical Development Department, West
Japan Railway Company
Research Areas: Vehicle Dynamics, Brake
System

Minoru MIYABE
Section Staff, Vehicle Design Section, Vehicle
Department, West Japan Railway Company
Research Areas: Brake Control, Body
Structure

Katsutoshi CHIKUMA
Section Staff, Vehicle Design Section, Vehicle
Department, West Japan Railway Company
Research Areas: Brake Control, Automatic
Train Control

Junya KAWAMURA
Researcher, Vehicle Performance Section,
Technical Development Department, West
Japan Railway Company
Research Areas: Powering and Braking,
Quality Control of Vehicle