Electro-pneumatic Blended Braking Control of Regenerative Brake and Air Brake based on Estimated Adhesion Coefficient

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Trains require high deceleration and stable traveling performance. Improvement in adhesion characteristics is, thus, very important for electric trains. We have previously proposed an anti-slip/skid re-adhesion control system that is based on a disturbance observer and possesses a high adhesion force utilization ratio. In the present work, we focus on the deceleration mode. Generally, a train has an electric regenerative brake (electric brake) and an air brake (mechanical brake). Under wet railway track conditions, the regenerative brake may be suspended because of the air brake response. This paper proposes a regenerative brake priority control and an electro-pneumatic blended braking control based on an estimated adhesion coefficient. Furthermore, this paper evaluates and discusses regenerative brake priority control using numerical simulations.

Keywords: disturbance observer, electro-pneumatic blended braking control, re-adhesion control, train, adhesion coefficient

1. Introduction

Railways are an important transportation infrastructure systems. Electric commuter trains containing multiple electric units are particularly useful for mass transportation in cities with a large population. The drive system of an electric commuter train must have a robust and advanced anti-slip/skid control system. Many studies have focused on overcoming this problem (11)-(13). We have previously proposed a new anti-slip/skid re-adhesion control system for an electric commuter train, that is based on a disturbance observer (14)-(16). In general, the expected adhesion coefficient is set for the motion of railway cars, and a deceleration plan is designed on the basis of this coefficient (16)-(18). Electric commuter trains use both a regenerative brake and an air brake at high speeds. Therefore, an electro-pneumatic blended brake control called “priority air supplement control of trailer coach” is employed for efficient use of the regenerative brake. Under normal rail conditions, obtaining an adhesion coefficient in excess of the expected adhesion coefficient is not a problem. However, when the railway tracks become wet because of rain or snow, the designed acceleration/deceleration characteristics may not be obtained. Furthermore, depending on the difference in the responses of the regenerative brake and air brake, the former may fall into abeyance (11). Therefore, cooperative control of the regenerative brake and air brake methods has been proposed (12).

To realize fine re-adhesion control, we examined an electro-pneumatic blended brake control, while considering the air brake characteristics. In particular, we considered the priority air supplement control of the trailer coach, which is a type of electro-pneumatic blended brake control (19). This paper proposes a “regenerative brake priority control” (RBPC) scheme (14), for cooperative control of the regenerative and air brakes. We enhanced the performance of the electro-pneumatic blended brake control by developing both RBPC and braking control on the basis of adhesion coefficient estimation by the disturbance observer (15).

2. Two-Coach Train Model

2.1 Dynamics Model of a Train

Figure 1 shows numerical simulation models of two-coach trains: (a) a two-coach train model, that considers the horizontal, vertical, and pitch motions of each car body; (b) a bogie truck model of the motor coach with a parallel Cardan drive, in which the horizontal, vertical, and pitch motions for each mass point are considered; and (c) a bogie truck model for the trailer coach, in which, the horizontal, vertical, and pitch motions for each mass point are considered. In the two-coach train model, a tight coupler is added between the motor coach and trailer coach (18). The model considers the relative motion of each coach.

Figure 2 shows the adhesion characteristic between the rail and wheel, which depends on the train and skid velocities. The tangential force coefficient \( \mu \) refers to the instantaneous value of the adhesion characteristic. The adhesion coefficient \( \mu_{\text{max}} \) is equal to the peak value of the tangential force

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coefficient. The tangential force coefficient is normalized by the standard adhesion coefficient \( \mu_z \) \((V_t = 0 \text{ km/h})\).

The speed-tangential force coefficient characteristics in Fig. 2 are the same as those in Fig. 4 of Ref. (17). Reference (17) presents a detailed explanation of the speed-tangential force coefficient characteristics by making use of Refs. (18)–(20). Fig. 4 of Ref. (17) was obtained from Fig. 3 of Ref. (17), which is Fig. 3 in this paper. Figure 3 in this paper is based on Ref. (18)–(20). The curve characteristics of Fig. 3-(a) are determined from Refs. (18)–(19). The curve characteristics of Fig. 3-(b) are determined from Ref. (20). In Ref. (17) and this paper, the simulation model for re-adhesion control uses the specifications of series 205-5000 train. The results of Ref. (17) confirmed the validity of Fig. 2 with regard to the series 205-5000 train.

This dynamics model considers the travel resistance and static friction.

### 2.2 Re-adhesion Control with Regenerative Brake

Figure 4 shows the structure of the electrical anti-skid re-adhesion control system. An inverter controls four induction motors connected in parallel (4M1C). The inverter is driven by a speed sensor-less vector control \((21)\) and cross-coupling current control \((22)\). In the motor coach, the motor current is reduced when skidding occurs at each axle. The motor current then flows to other motors, and the electrical braking torque rises in the adhesive axle. Hence, in the motor coach, the four axles skid similarly at the same time when skidding occurs at each axle.

Figure 5 shows the anti-skid re-adhesion control algorithm. The equation of motion of the one-wheel conversion traction system is given by Eq. (1). The load torque \( \tau_L \) is equal to the momentary adhesion force between the drive wheel and rail,
\( J_m \) is the compound moment of inertia of the traction drive system, \( \tau_m \) is the output torque of the traction motor, and \( \hat{\omega}_m \) is the estimated angular velocity of the traction motor. If the inverter system of the train detects a skid phenomenon from the differential value of the estimated drive wheel velocity (estimated drive wheel acceleration), the momentary load torque \( \tau_L \) is estimated by the disturbance observer, as shown in Fig. 6 and Eq. (2). The symbol \( s \) refers to the Laplace operator, \( a \) is the pole of the disturbance observer, \( R_g \) is the gear ratio, \( \mu(V_s) \) is the tangential force coefficient, \( W \) is the axle weight, \( g \) is the acceleration of gravity, and \( r \) is the radius of the drive wheel. We set \( a = 100 \text{ rad/s} \) to obtain the necessary performance.

\[
J_m \frac{d}{dt} \hat{\omega}_m = \tau_m - \tau_L \hspace{1cm} (1)
\]

\[
\dot{\tau}_L = \frac{a}{s + a} (\tau_m - J_m s \hat{\omega}_m) \hspace{1cm} (2)
\]

\[
\tau_L = \frac{1}{R_g} \mu(V_s) W g r \hspace{1cm} (3)
\]

The regenerative torque decreases according to \( \tau_{m-\text{lim}} \). \( \tau_{m-\text{lim}} \) is defined in Eq. (4). \( \beta \) is the compensation coefficient for re-adhesion.

\[
\tau_{m-\text{lim}} = \beta \dot{\tau}_L \hspace{1cm} (4)
\]

After re-adhesion, the regenerative torque increases to the same level as \( \tau_{m-\text{rec}} \) which is defined by Eq. (5). These parameters were adjusted by the trial run \( ^{46} \).

\[
\tau_{m-\text{rec}} = a \beta \dot{\tau}_L \hspace{1cm} (5)
\]

2.3 Anti-skid Brake Control with Air Brake The air brake operates by using air pressure and the friction between the brake pad and drive wheel tread. Figure 7 shows the air brake model. This model considers the dead time of the electro-magnetic valve (\( \text{dead time}_1, \text{dead time}_2 \)) and the air pressure response \( (\tau_1, \tau_2) \). The brake cylinder pressure (BCP) is controlled by the discharge valve and lockout valves. Table 1 lists the time constant and dead time of the discharge valve and lockout valves. The values used herein are calculated from past vehicle test data \( ^{22} \).

Figure 8 shows the BCP pattern for anti-skid brake control. The trailer coach air brake system has individual control for each axle. The angular acceleration signal of the wheels is calculated by a PG mounted to each axle. When skidding is detected in each axle by the angular acceleration signal, anti-skid re-adhesion control is performed. Figure 8 shows the BCP pattern for anti-skid brake control.

3. Electro-pneumatic Blended Braking Control System

3.1 Brake Structure of Two-Coach Train The motor coach has a regenerative brake and air brake. The trailer coach has only an air brake. The regenerative brake is the parallel drive system of the four-axles. The air brake is the individual control system of the four-axles.

3.2 Air Supplement Control Figure 9 shows the characteristic of the regenerative brake. The regenerative brake does not possess sufficient brake force in the high-speed range, and the train still requires an air brake. Thus, the total brake force is the sum of the regenerative and air brake forces. The electro-pneumatic blended braking control supplements the regenerative brake with an air brake \( ^{23} \). Figure 10 shows a block diagram of the air supplement control system. The brake command is given to the inverter and electro-pneumatic conversion valve by the brake operating device, and a signal equivalent to the regenerative brake torque is fed back to the brake operating device from the inverter. Figure 11 shows the priority air supplement control of the trailer coach. This technique extends the range of the air supplement control to the trailer coach \( ^{24} \), as shown in Fig. 10. The priority air supplement control of the trailer coach has only an air brake.
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Fig. 10. Air supplement control system

Fig. 11. Priority air supplement control of trailer coach

Fig. 12. Priority air supplement control of trailer coach. (Under conditions of low adhesion coefficient)

Fig. 13. Regenerative brake priority control

Fig. 14. Simulation result of regenerative electric energy

Table 2. Simulation conditions

<table>
<thead>
<tr>
<th>parameter</th>
<th>conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial velocity[km/h]</td>
<td>100</td>
</tr>
<tr>
<td>design deceleration[km/h/s]</td>
<td>3.5</td>
</tr>
<tr>
<td>standard adhesion coefficient $\mu_z$</td>
<td>0.220-0.110</td>
</tr>
</tbody>
</table>

coach is a type of electro-pneumatic blended braking control. First, the regenerative brake applies the full brake force, and the inverter generates a regenerative braking torque equivalent signal (RB). Second, the trailer coach air brake applies the difference between the total brake force and RB. Third, the motor coach air brake applies the rest of the total brake force. Thus, the brake force is distributed through a three-brake system.

Decreasing the use of the motor coach air brake enables efficient use of the regenerative brake. This electro-pneumatic blended braking control is applicable to a two-coach electric commuter train.

3.3 RBPC

Under conditions such as a wet railway track with a low adhesion coefficient, the motor coach air brake applies the full brake force, and RB is generated by the inverter. When skidding occurs in the motor coach and re-adhesion control is performed by the regenerative brake, the regenerative brake torque needs to be reduced. In this case, the shortage in braking torque comes from the trailer coach air brake.

Under conditions with a high adhesion coefficient, this shortage is supplemented by the trailer coach air brake. However, when the adhesion coefficient is low, the motor coach air brake is applied since the shortage cannot be handled by the trailer coach.

The motor coach has different response brake forces. The skid detection and response speed of the regenerative brake are better than those of the air brake. Hence, anti-skid re-adhesion control is performed with the regenerative brake during skidding. The regenerative brake may fall into abeyance owing to the excessive response of the motor coach air brake, only after the priority air supplement control of trailer coach is applied.

Our proposed RBPC is shown in Fig. 13; it is a technique that improves RB, which is shown in Fig. 10. RBPC is included in the priority air supplement control of the trailer coach. During anti-skid re-adhesion control with the regenerative brake, RBPC holds the RB at the moment when skidding is detected. Therefore, any decrease in the regenerative brake torque is unaffected by the air brake command.

3.4 Effect of RBPC

In this study, we assumed the simulation conditions listed in Table 2. A two-coach electric commuter train decelerates by braking at high-speed: the train accelerates until it reaches a speed of 102 km/h; it coasts until it reaches a speed of 100 km/h; and it decelerates until it reaches a speed of 0 km/h. In this study, we focus on the deceleration mode. In the simulation, the step size of the standard adhesion coefficient $\mu_z$ is set as 0.005. We perform simulations with and without RBPC, and evaluate and discuss its effects.

Figure 14 shows the amount of regenerative electric energy for each simulation result. When RBPC is not applied, the amount of regenerative electric energy is greatly reduced when the standard adhesion coefficient is less than 0.155. In contrast, when RBPC is applied, the amount of regenerative electric energy increases when the standard adhesion coefficient is low.
coefficient is lower than 0.155. When the standard adhesion coefficient is 0.140, the amount of regenerative electric energy is doubled in the case when RBPC is applied.

Figures 15 and 16 show simulation results when the standard adhesion coefficient is 0.140, without and with RBPC, respectively. Starting from the top, each graph shows the regenerative brake torque, motor coach air BCP, wheel acceleration, wheel speed, trailer coach air BCP, and wheel speed. As shown in Fig. 15, without RBPC, skidding occurs in the trailer coach, and anti-skid brake control is applied by the air brake. The regenerative brake is fallen into abeyance by the brake command given to the motor coach air brake. As shown in Fig. 16, with RBPC, skidding occurs in the trailer coach, and anti-skid brake control is applied by the air brake. However, the excessive rise in air brake pressure is reduced by RBPC, so the regenerative brake torque is maintained. Under this condition, the braking time is reduced by 2 s.

Figure 17 shows the average deceleration rate for each simulation result. The superiority of RBPC is again confirmed with regard to the amount of regenerative electric energy. When the standard adhesion coefficient is 0.140, re-adhesion control is applied by the regenerative brake with RBPC. Consequently, the adhesion force is more effectively utilized than when anti-skid brake control is operated by the air brake.

However, applying RBPC when the standard adhesion coefficient is more than 0.150 degraded the deceleration performance which satisfies the designed deceleration deteriorates. This is because, despite trailer coach having sufficient adhesion, the increase in air brake pressure for not only the motor coach but also the trailer coach is suppressed by RBPC.

4. RBPC Considering Adhesion Coefficient

4.1 Derivation of Expectancy Adhesion Coefficient

The expected adhesion coefficient \( \mu_{ex} \) is derived; this is the adhesion coefficient that theoretically satisfies the designed deceleration. When the priority air supplement control of the trailer coach is operated, skidding first occurs in the motor coach because the brake command is allocated on a priority basis to the motor coach regenerative brake. The shortfall in the total brake force is supplemented by the trailer coach air brake. Therefore, the lower limit of the adhesion coefficient when skidding does not occur in the trailer coach is defined as the expected adhesion coefficient \( \mu_{ex} \).

The motion equation of the 1M1T unit is shown in Eq. (6). \( \tau_b \) is the conversion total brake force of a wheel axle, \( \tau_{LM} \) is the adhesion force of a motor coach axle, \( \tau_{LT} \) is the adhesion force of a trailer coach axle, \( M_M \) is the motor coach mass, \( M_T \) is the trailer coach mass, and \( v_{ref}^{ref} \) is the designed deceleration.

\[
(M_M + M_T) \dot{v}_{ref}^{ref} = \frac{\tau_{LM}}{R_W} + \frac{\tau_{LT}}{R_W} \quad \quad \quad \quad (6)
\]

On the basis of Eq. (1), \( \tau_{LM} \) and \( \tau_{LT} \) are represented by Eq. (7) and Eq. (8).

\[
z \tau_{LM} = z \tau_e + \tau_{air M} - \left( \frac{z^2 J_R + J_W}{R_W} \right) \frac{\dot{v}_{ref}^{ref}}{R_W} \quad \quad \quad \quad (7)
\]

\[
z \tau_{LT} = \tau_{air T} - J_W \frac{\dot{v}_{ref}^{ref}}{R_W} \quad \quad \quad \quad (8)
\]

On the basis of Eq. (7) and Eq. (8), the total brake force for the entire unit is represented by Eq. (9).

\[
\tau_b = \left\{ \frac{R_W}{4} (M_M + M_T) + \frac{1}{R_W} (z^2 J_R + 2 J_W) \right\} \dot{v}_{ref}^{ref} \quad \quad \quad \quad (9)
\]

When the brake force is equal to the adhesion force, the expected coefficient \( \mu_{ex} \) is defined as its adhesion coefficient \( \mu_{max} \). Here, \( \tau_{LM} \) and \( \tau_{LT} \) are represented by Eq. (10) to
On the basis of Eq. (6), Eq. (10) to Eq. (11), the total brake force for the entire unit is also represented by Eq. (12).

\[ \tau_b = \left( \mu_{ex} \frac{gR_w}{4} (M_M + M_T) + \frac{1}{R_w} (z^2 J_R + 2 J_g) \right) \dot{v}_{ex} \tag{12} \]

The right-hand sides of equations Eq. (9) and Eq. (12) are compared to define the expected adhesion coefficient in Eq. (13).

\[ \mu_{ex} = \frac{\dot{v}_{ex}}{g} \tag{13} \]

We set the designed deceleration to be 3.5km/h/s; \( \mu_{ex} \) becomes 0.0992. Figure 18 shows the adhesion coefficient corresponding to the standard adhesion coefficient \( \mu_e \) and train speed \( \dot{v} \). \( \mu_{ex} \) is the adhesion coefficient when the train is stationary. The expected adhesion coefficient \( \mu_{ex} \) is represented as a dotted line in Fig. 18.

### 4.2 Applied Condition of RBPC

Given the condition that skidding of the train does not occur at all during braking from a speed of 100km/h, the adhesion coefficient at this speed must be greater than 0.0992. We use the train speed-tangential force coefficient characteristics shown in Fig. 2. As shown in Fig. 18, the adhesion coefficient decreased to 65.2% when the train speed is 100km/h. Consequently, the zero-speed expected adhesion coefficient \( \mu_{ex} \) obtained by converting \( \mu_{ex} \) into \( \mu_e \) is 0.152. As shown in Fig. 17, \( \mu_{ex} \) is the inflection point of the deceleration performance. However, Fig. 18 shows that even if \( \mu_e \) is smaller than \( \mu_{ex} \), the trailer coach has sufficient adhesion depending on the traveling speed. Therefore, we propose Eq. (14) as the condition for applying RBPC. Here, \( \mu_{max} \) is the estimated adhesion coefficient when skidding is detected by the disturbance observer.

\[
\text{if } \mu_{max} \leq \mu_{ex} \text{ then RBPC : ON} \tag{14} \\
\text{else RBPC : OFF}
\]

By applying Eq. (14), when the trailer coach has sufficient adhesion, only the priority air supplement control of trailer coach is operated. When the brake command is given to the motor coach air brake because of insufficient adhesion in the trailer coach, RBPC is applied. This paper proposes operation-selection-type RBPC based on Eq. (14).

### 5. Evaluation with Numerical Simulation

#### 5.1 Simulation Conditions

The simulation is performed under the conditions listed in Table 2: a two-coach electric commuter train decelerates by braking at a high speed. The driving pattern of the train in the following paragraph. First, the train accelerates to a speed of 102 km/h. Second, it coasts until it reaches a speed of 100 km/h. Third, the train decelerates until it reaches a speed of 0 km/h. This study focuses on the deceleration mode. In the simulation, the step size of the standard adhesion coefficient \( \mu_e \) is set to 0.005. We perform simulations with and without RBPC, and evaluate and discuss.

#### 5.2 Simulation Result

A numerical simulation of operation-selection-type RBPC was performed under the conditions listed in Table 2. The simulation results at \( \mu_e = 0.180 \) in Fig. 18 are shown in Fig. 19, Fig. 20, and Fig. 21. The conventional method is defined as priority air supplement control of the trailer coach. Under the condition of \( \mu_e = 0.180 \), RBPC do not operate because the adhesion coefficient exceeded the expected adhesion coefficient in all areas, the average deceleration rate is consistent with the conventional method. Therefore, the behavior of the operation-selection-type RBPC, as shown in Fig. 19 is consistent with that of the conventional method shown in Fig. 21.

We consider the area where the standard adhesion coefficient \( \mu_e \) is smaller than the zero-speed expected adhesion coefficient \( \mu_{ex} \). The simulation results at \( \mu_e = 0.140 \) in Fig. 18 are shown in Fig. 22, Fig. 23, and Fig. 24. With operation-selection-type RBPC, the time until the train becomes stationary is relatively short compared with the case when RBPC is applied. At high speeds, implementation of re-adhesion control by the regenerative brake is identical to that in the case with RBPC. However, at low speeds, the trailer coach air brake command is enhanced in the case without RBPC, which increased the deceleration rate.

The simulation results at \( \mu_e = 0.120 \) in Fig. 18 are shown in Fig. 25, Fig. 26, and Fig. 27. Since the adhesion coefficient is very low, the motor coach air brake command is enhanced, the regenerative brake is fallen into abeyance, and anti-skid brake control is applied because of the air brake in both coaches. Hence, the results for operation-selection-type RBPC coincide with the results for RBPC. Therefore, even operation-selection-type RBPC, it is not possible to avoid the regeneration-canceled phenomena when the adhesion coefficient is very low.

Figure 28 shows the average deceleration rate for each simulation result. Figure 29 shows the amount of regenerative electric energy for each simulation result. When the standard adhesion coefficient \( \mu_e \) is more than the zero-speed expected adhesion coefficient \( \mu_{ex} \), the average deceleration rate coincides with that obtained by using the conventional method. These results imply that RBPC is not operated. Similarly, the amount of regenerative electric energy coincides with that

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![Fig. 18. Characteristics of adhesion coefficient](image-url)
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Fig. 19. Simulation result with operation-selection-type RBPC ($\mu_z = 0.180$)

Fig. 20. Simulation result with RBPC ($\mu_z = 0.180$)

Fig. 21. Simulation result with conventional method ($\mu_z = 0.180$)

Fig. 22. Simulation result with operation-selection-type RBPC ($\mu_z = 0.140$)

Fig. 23. Simulation result with RBPC ($\mu_z = 0.140$)

Fig. 24. Simulation result with conventional method ($\mu_z = 0.140$)
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**Fig. 25.** Simulation result with operation-selection-type RBPC ($\mu_z = 0.120$)

**Fig. 26.** Simulation result with RBPC ($\mu_z = 0.120$)

**Fig. 27.** Simulation result with conventional method ($\mu_z = 0.120$)

**Fig. 28.** Simulation result of average deceleration

**Fig. 29.** Simulation result of regenerative electric energy obtained with the conventional method and is slightly lower than that for RBPC. However, this phenomenon is considered to have little impact because the amount of regenerative electric energy in this area is very large.

When the standard adhesion coefficient $\mu_z$ is less than the zero-speed expected adhesion coefficient $\mu_{z-ex}$, the average deceleration rate is nearly equal to that for RBPC. In addition, through the application of the RBPC, the amount of regenerative electric energy should be improved compared to that for the conventional method.

**6. Conclusion**

Applying RBPC can prevent the abeyance of the regenerative brake with low adhesion coefficients. For example, when the standard adhesion coefficient is 0.140, the regenerative electric energy increases by as much as a factor of 2.2. Thus, RBPC makes efficient use of the regenerative brake. With RBPC, the motor coach operates anti-skid re-adhesion control using the regenerative brake. Consequently, the average deceleration rate is improved. However, when the standard adhesion coefficient is more than 0.150 with RBPC, the deceleration performance deteriorates.

In this paper, we define the expected adhesion coefficient and propose a new operation-selection-type RBPC. This paper evaluated and discussed the operation-selection-type RBPC using numerical simulations. The results showed that the average deceleration rate for operation-selection-type RBPC was consistent with that for the conventional method. Therefore, the average deceleration rate for high adhesion...
coefficients was well improved and the regenerative electric energy for low adhesion coefficients was high.

References


Appendix

1. Real Trains Running Experimental Data and Numerical Simulation Results for Anti-skid Re-adhesion Control

App. Fig. 1 shows the actual experimental data of the anti-skid re-adhesion control system for the series 205-5000 of the East Japan Railway Company; they are taken from Ref. (8). The detailed calculation method of the utilization ratio of the adhesion force is given by Eq. (6) and Fig. 7 of Ref. (8). In the experimental results of Ref. (8), the calculated utilization ratio of the adhesion force was 91.2%. App. Fig. 2 shows the simulation results for anti-skid re-adhesion control using the specifications of the series 205-5000 train. App. Fig. 2 is the same as Fig. 10 in Ref. (8). The calculated utilization ratio of the adhesion force is approximately 91.4% in app. Fig. 2. The value of 91.4% in app. Fig. 2 is nearly equal to the value of 91.2% in app. Fig. 1 by using data from actual experiments performed with a running train. Therefore, the simulation results reflect the behavior of real trains. The equivalent simulation model in this paper is the same as that of Ref. (8). The simulation results based on a dynamics model of motor coach and trailer coach confirmed the performance and usefulness of priority air supplement control.
app. Fig. 1. The actual experimental data of anti-skid re-adhesion control, Series 205-5000\(^{(8)}\).

app. Fig. 2. The Simulation result of anti-skid control for the electric multiple units, Series 205-5000\(^{(8)}\).

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