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The design of electronically controlled pneumatic brake signal propagation mode for electronic control braking of a 30,000-ton heavy-haul train

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Abstract

This paper takes 30,000-ton heavy-haul trains as the research object, and studies the propagation characteristics, train braking ability and longitudinal impulse level of three ECP electronic control signal Propagation modes of segmented electro-pneumatic braking under different lag times. The difference between the train's use of segmented electro-pneumatic braking and air braking in the long ramp operation method is compared. The results show that the best way is when the leading control locomotive sends the ECP signal backward and the slave control locomotive sends the ECP signal both forward and backward. Compared with the worst mode that only the leading control locomotive propagates the ECP signal backward, the coupler force can be reduced by 46.5%, the time difference between the slowest and fastest action vehicles can be reduced by 60.5%, and the emergency braking distance can be reduced by 1.2%. With the increase in the lag time of the slave control locomotive, the differences in the braking capacity and longitudinal impulse level of the three ECP electronic control signal propagation modes decrease. The effectiveness of the slave control locomotive's ability to send ECP signals is closely related to the lag time of the leading and slave control locomotives. Compared with pure air braking, segmented electro-pneumatic braking can delay the braking times of the last two brakes by 32.6 s and 83.7 s,respectively, during the three-cycle braking, and the starting time of relief can be delayed by 12.7 s, 89.8 s and 16.9 s respectively, and the maximum coupler force can be reduced by 30.1%. The research work of this paper can provide reference for the formulation of electro-pneumatic braking scheme of 30,000-tons heavy-haul train.

Keywords

Heavy-haul train, segmented electro-pneumatic braking, long ramp, cycle braking, lag time

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Introduction

The transport capacity of heavy-haul railways in China can no longer meet the demand with the development of the social economy, so it is urgent to improve the transport capacity of heavy-haul railways, and increasing the length of heavy-haul trains is the most effective measure to improve the transport capacity of heavy-haul railways at present. Compared with the 20,000-ton heavy-haul trains running in China, the operation of 30,000-ton heavy-haul trains will greatly enhance China's transportation capacity on heavy-haul railways. A 30,000-ton heavy-haul train with a huge weight and a length of several kilometers will inevitably have a strong longitudinal impact behavior during traction, operation and braking, resulting in a great longitudinal coupler force, which is prone to accidents such as decoupling and broken couplers, posing a serious threat to the safety of train operation.[1] Therefore, the problem of coupler force should be solved first when running a 30,000-ton heavy-haul train. One of the main measures to reduce the coupler force of the 30,000-ton heavy-haul train is to adopt electro-pneumatic braking, which is different from that of the United States and is a segmented electro-pneumatic braking system completely compatible with the existing air braking in China.[2] The segmented electro-pneumatic brake has completed the stationary test and line test of 200,000 km for the train. At present, the train test shows that segmented electro-pneumatic braking can effectively reduce the time difference between the front and rear braking and alleviation of long and heavy-haul trains, break the limitations of air braking system and improve the driving safety of heavy-haul trains. Therefore, it is of great significance for the development of China's heavy-haul

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railways to carry out the research on segmenting electro-pneumatic braking of 30,000-ton heavy-haul trains.

Many scholars have studied the longitudinal dynamics of trains. Rao[3] established a mathematical model earlier, and studied the transient response of train coupler force under different locomotive operation modes. Geike[4] analyzed the coupler forces during train rescue and multi-train coupling using the established unitized combined train model. Belforte[5] used MATLAB simulation software to simulate the longitudinal dynamics of heavy haul railways in Europe, and explored the impact of different marshalling modes on the safety of train operation. Janarthanan[6] established a simulation model for the transient analysis of longitudinal dynamics of heavy haul trains. Through this model, the acceleration and braking performance of trains running on different rail surfaces were studied. Serajian R et al.[7] considered that the train braking asynchrony will lead to a large longitudinal force of the train, and used MATLAB simulation to study the influence of different train lengths on the longitudinal dynamics of the train. Specchia S et al.[8,9] established the model of air braking system and locomotive automatic braking valve, air brake pipe and vehicle control unit (CCU), studied the air flow in air braking and release of brake pipe, and predicted the braking performance of train. Ansari and Esmailzadeh[10,11] made clear the influence of the characteristic parameters of coupler and retarder on the longitudinal dynamics of trains based on the nonlinear time domain model, and compared and analyzed the parameters of different coupler and retarder, and optimized the train formation mode. Cole et al.[12] proposed a co-simulation method of locomotive traction control, vehicle system dynamics and train longitudinal dynamics, and carried out experimental verification. Zhao et al.[13] studied the longitudinal force of 20,000 tons "1 + 1" marshalling combination train under braking condition, and pointed out that the signal lag time of the slave control locomotive should be within 4 s to ensure the safe operation of the heavy haul train on Daqin line. Wei et al.[14,15] developed the Train Air Brake and Longitudinal Dynamics Simulation System (TABLDSS), which is widely used in the field of train longitudinal dynamics analysis, air brake system structure optimization, accident analysis and operation optimization.

Most of the existing studies are aimed at the longitudinal impulse of heavy-haul trains caused by air braking and the corresponding handling optimization, and there are relatively few studies on the influence of train electro-pneumatic braking signal propagation mode on longitudinal impulse. At present, the test conditions for segmented electro-pneumatic braking of 30,000-ton trains are not available, and the selection of propagation modes needs theoretical research results. Therefore, it has obvious advantages to model a new segmented electro-pneumatic braking system with various ECP signal propagation modes for 30,000-ton trains and study the braking and longitudinal impulse characteristics of this combined braking system by using simulation methods.

In this paper, the train air braking and longitudinal dynamics simulation system (TABLDSS) is used to simulate and analyze the propagation characteristics, train braking capacity and longitudinal impulse level of the three ECP electronic control signal propagation modes of segmented electro-pneumatic braking, and the optimal ECP electronic control signal propagation mode is selected, and the influence of the lag time of the slave control locomotive on the above characteristics of the three propagation modes is analyzed. This paper analyzes the difference between segmented electro-pneumatic braking and air braking on long ramps, taking the "three brakes" cycle braking in Nanwan-Xiaojue District of Shuohuang Line as an example. The research work of this paper can provide reference for the formulation of electro-pneumatic braking scheme of 30,000-tons heavy-haul train.

Train air brake and longitudinal dynamics simulation system

This paper is based on the Train Air Brake and Longitudinal Dynamics Simulation System developed by Dalian Jiaotong University. The simulation system automatically forms characteristic line method grid according to the pipe parameters. Train parameters are inputted in the form of a clear and intuitive dialog box. With the calculation of up to four locomotives, each locomotive can be applied to asynchronous control instructions. Due to the detailed model of the distribution valve, the influence of various parameters on the braking performance and longitudinal impact of the train can be analyzed. This system provides basic theory and practical tools for analyzing the train longitudinal impulse mechanism and optimizing the braking and draft gear system, and achieved excellent results in calculation accuracy and speed in the international longitudinal dynamics evaluation in 2017.[16]

Compressed air-flow equation in pipes

The calculation of air-flow in braking system mainly includes the calculation of pressure in pipeline, boundary and chamber. State of gas in pipeline is obtained according to mass conservation equation, momentum conservation equation and energy conservation equation of gas flow in pipeline. The equation of state of gas at non-boundary points in the pipeline is as follows:

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \rho \dfrac{\partial u}{\partial x} + u \dfrac{\partial \rho}{\partial x} + \dfrac{\rho u}{F} \times \dfrac{dF}{dx} = 0 \\ \dfrac{\partial u}{\partial t} + u \dfrac{\partial u}{\partial x} + \dfrac{1}{\rho} \dfrac{\partial p}{\partial x} + \dfrac{4f}{D} \times \dfrac{u^2}{2} \times \dfrac{u}{|u|} = 0 \\ \dfrac{\partial \rho}{\partial t} + u \dfrac{\partial \rho}{\partial x} - a^2 \dfrac{\partial \rho}{\partial t} - a^2 u \dfrac{\partial \rho}{\partial t} - (k-1)\rho \left(q + u \dfrac{4f}{D} \times \dfrac{u^2}{2} \times \dfrac{u}{|u|} \right) = 0 \end{cases} \tag{1}$$

In these equations, ρ, u and p are the gas density, velocity and pressure, respectively; a is the sound velocity; D is the hydraulic diameter of the fluid, F is the cross-sectional area of the tube, f is the friction coefficient of the inner wall of the tube, k and q are the gas-specific heat ratio and heat exchange quantity per unit time, respectively; x is the distance and t is the time.

Equation (1) has no analytical solution and needs to be solved by numerical method. The characteristic line method can be used.[17] The physical quantities of each gas are transformed into Riemann variables and entropy expressions. After dimensionless transformation, three characteristic line directions and corresponding incremental expressions can be obtained:

Along the λ characteristic line:

$$d\lambda = \frac{A}{A_A}dA_A - \frac{k-1}{2}\frac{AU}{F}\frac{dF}{dX}dZ + \frac{(k-1)^2}{2}\frac{qX_{ref}}{a_{ref}^3}\frac{1}{A}dZ - \frac{k-1}{2}\frac{2fX_{ref}}{D}U^2\frac{U}{|U|}\left[1-(k-1)\frac{U}{A}\right]dZ \quad (2)$$

Along the β characteristic line:

$$d\beta = \frac{A}{A_A}dA_A - \frac{k-1}{2}\frac{AU}{F}\frac{dF}{dX}dZ + \frac{(k-1)^2}{2}\frac{qX_{ref}}{a_{ref}^3}\frac{1}{A}dZ + \frac{k-1}{2}\frac{2fX_{ref}}{D}U^2\frac{U}{|U|}\left[1-(k-1)\frac{U}{A}\right]dZ \quad (3)$$

The characteristic line along the entropy trace:

$$dA_A = \frac{k-1}{2}\frac{A_A}{A^2}\left[\frac{qX_{ref}}{a_{ref}} + \frac{2fX_{ref}}{D}|U|^3\right]dZ \quad (4)$$

In these equations, λ and β are Riemann variables, A_A is entropy, X, Z, U, A and F are dimensionless distance, dimensionless time, dimensionless velocity, dimensionless sound velocity and dimensionless area, k is specific heat ratio, f is wall friction, X_{ref} is reference length and a_{ref} is reference sound velocity.

This equation cannot fully obtain all the parameters of the pipeline boundary points. Some boundary conditions do not change with time, such as the joint between the train brake pipe and the branch pipe. At this time, the boundary condition equation must be used to solve the parameters, and the corresponding boundary equation can refer to.[14]

Single vehicle braking system mode with electronic control device

The segmented electro-pneumatic brake is based on the principle of electro-pneumatic exhaust device and gas flow theory. It is a new electro-pneumatic brake system. It realizes the rapid exhaust capacity of some vehicles by installing electronic control devices in some vehicles and accelerates the braking synchronization of trains. Different from the ECP direct electric control braking system, the device does not control the auxiliary air cylinder to charge the brake cylinder, but controls the brake pipe exhaust. Therefore, the device is fully compatible with the existing braking system in China and adapts to the air braking system of freight trains in China. And the segmented electro-pneumatic brake has the characteristics of air signal and electric signal propagation together.

The grouping concept is that the train does not need to install an electronically controlled exhaust device for each vehicle and is considered to be composed of many groups of short trains. Each group of short train is equipped with an electronically controlled device, which can greatly reduce the cost of vehicle transformation. As shown in Figure 1(a), where J denotes the locomotive, Z1... Z2... Zn denotes the installation position of the electronic exhaust device, N1... N2... Nn denotes the number of groups contained in the column. Locomotive J is located in the first position of the train, and the first electric control exhaust device is installed in the second position, that is, the first vehicle. According to a factory design of every two vehicles as a group, so the second electronic control exhaust device should be installed in the third section of the vehicle, the n electronic control exhaust device should be located in the 2n−1 section of the vehicle. If the total number of vehicles in the train is odd, in order to prevent the train from emergency braking, the last group is specified as three vehicles. After dividing the train into several groups, an electronically controlled exhaust device, a relay mechanism and a balanced reservoir are added to each group without changing the original air brake system. The exhaust device controls the exhaust port of the exhaust device through the radio signal emitted by the receiver vehicle. A factory in China is preparing to produce the first batch of segmented electro-pneumatic brake vehicles. In the early stage of operation, electronically controlled exhaust devices were installed on each vehicle for safety reasons. In this paper, each vehicle is equipped with an electronically controlled exhaust device when setting parameters.

The physical model of segmented electro-pneumatic braking device for a single vehicle is shown in Figure 1(b). The operating principle of the electric control device is described in detail in reference 18. Total pipes in one vehicle are six, two pipes are main brake pipe, one is branch pipe, three are connecting pipes between valve and auxiliary reservoir, valve and brake cylinder, valve and accelerating release reservoir, respectively. Six chambers are upper chamber and lower chamber of main valve, emergency room, auxiliary reservoir, brake cylinder, accelerating release reservoir. There are resistant unit models in the each end of main brake pipe to simulate the hose connectors and angle cock. The model has nine orifices to simulate the inner channel of the valve. The specific role of each orifice can be seen in Reference 19. The nine orifices' states (close/open) and sizes are determined by the position of the moving parts of the valves. It is be calculated by the procedure according to the principle of 120 distribution valve. Now, almost all the functions of 120 distribution valves can be realized in the model.

This paper focuses on the introduction of the hole φ10–φ12 of the electronic control exhaust device, that is, the action principle of the electronic control device and the corresponding calculation formula. During braking, the electric control signal sent by the locomotive directly controls the φ10 area of the exhaust port of the balancing reservoir in the electric control exhaust device. The relay valve determines the working state of the relay valve according to the pressure difference between the upper cavity of the balancing reservoir and the distribution valve. When the pressure difference reaches a certain condition, the φ11 hole is opened to realize the purpose of discharging the compressed air of the brake pipe into the atmosphere through the upper chamber of the main valve, and realize the remote control decompression function of the brake pipe. When the pressure reduction of the balancing reservoir reaches the pressure reduction set by the locomotive command, the exhaust port φ10 of the balancing

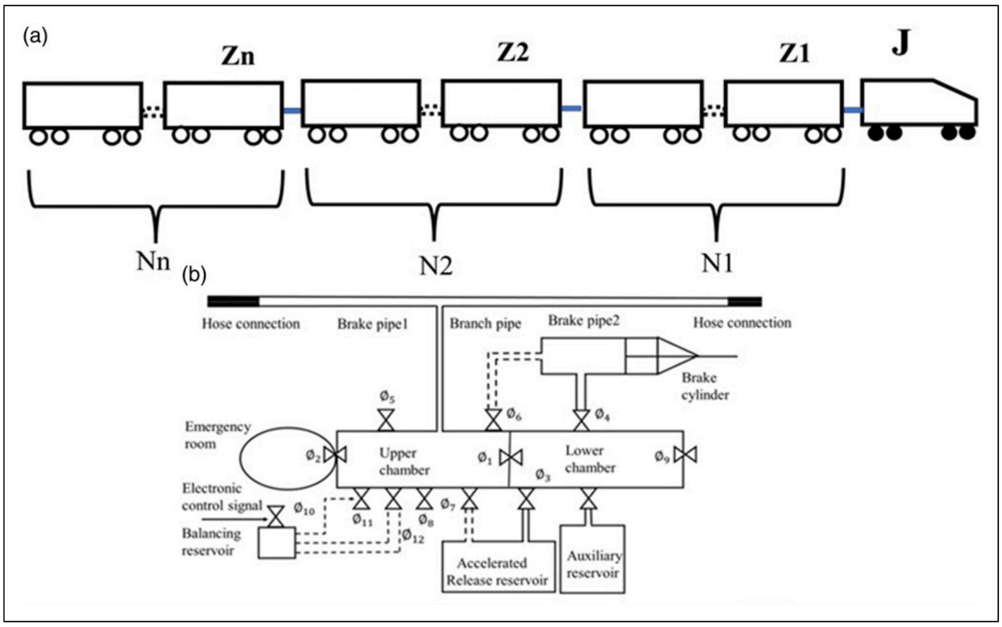

Figure 1. Segmented electro-pneumatic braking diagram. (a) The grouping of train segmented electro-pneumatic braking system, (b) Single vehicle braking system mode with electronic control device.

reservoir is closed. After the opening of the exhaust port φ11 of the brake pipe, as the pressure of the brake pipe decreases, the pressure difference between the equilibrium air cylinder and the brake pipe decreases continuously. When the two are balanced, the relay valve closes the φ11 hole and the brake pipe stops remote decompression (to distinguish it from the brake pipe local decompression and the brake pipe decompression caused by the locomotive exhaust port decompression). When the electronic control device receives the remote control command of the locomotive gate, the remote control device will open the φ12 hole. At this time, the φ12 hole is connected with the equalization air cylinder through a virtual pipeline (dotted line in the figure). At this time, the air in the brake pipe flows into the equalization air cylinder through the upper chamber of the distribution valve to realize the equalization air cylinder charging function. When the final pressure of the balancing reservoir and the brake pipe is balanced, the φ12 hole of the equalization air cylinder is closed, and the equalization air cylinder stops charging. At the same time, when the electronic control device receives the locomotive relief signal, the φ7 hole is opened to realize the function of accelerating the relief cylinder to fill the upper cavity of the main valve (refill the brake pipe).

The exhaust area of the balancing reservoir is expressed as follows:

$$\phi_{10} = \begin{cases} f_B(\Delta P_{end}, \Delta P_B) & \Delta P_B < \Delta P_{end} \\ 0 & \Delta P_B \geq \Delta P_{end} \end{cases} \tag{5}$$

The function f_B is the function of the area of the exhaust port of the balancing reservoir. When the electronic control exhaust command is initially received, the initial exhaust port of the balancing reservoir is determined by the locomotive pressure reduction, and then as the pressure reduction of the balancing reservoir approaches the final pressure reduction, the exhaust port area gradually decreases until it is closed. ΔP_B and ΔP_{end} are the pressure reduction of the balancing reservoir and the locomotive command pressure reduction, respectively.

The opening of the brake pipe exhaust port is calculated as follows:

$$\phi_{11} = \begin{cases} f_T(\Delta P_T, \Delta P_B) & \Delta P_T < \Delta P_B \\ 0 & \Delta P_T \geq \Delta P_B \end{cases} \tag{6}$$

The function f_T is a function of the area of the exhaust port of the brake pipe, and its opening area is related to the difference between the pressure reduction of the brake pipe and the pressure reduction of the balancing reservoir. When the pressure reduction of the brake pipe is equal to the pressure reduction of the balancing reservoir, the exhaust port is closed. ΔP_T is the pressure reduction of the brake pipe.

Calculation method of air inlet of balancing reservoir:

$$\phi_{12} = \begin{cases} f_{Bf}(\Delta P_T - \Delta P_B) & \Delta P_B < \Delta P_T \\ 0 & \Delta P_B \geq \Delta P_T \end{cases} \tag{7}$$

When the electric control device receives the relieved electric signal instruction, if the pressure of the brake pipe is higher than the pressure of the balancing reservoir, the intake area of the f_{Bf} expression is used to charge the balancing reservoir, and the opening area is determined by the pressure difference between the balancing reservoir and the brake pipe. ΔP_B and ΔP_T are the pressure of balance air cylinder and brake pipe respectively.

Simulation model of 30,000 tons heavy haul train

The simulation uses the 30,000-ton heavy haul train marshalling method as shown in Figure 2, using the 1+1+1+1 (HXD1+108*C80+HXD1+108*C80+HXD1+108*C80+HXD1) marshalling method. (1) Figure 2(a) shows that only the leading locomotive sends the electronically controlled ECP signal backward. (2) Figure 2(b) shows that the leading locomotive sends the electronic control ECP signal backward, and the slave control locomotive sends the electronic control signal backward after receiving the signal from the leading locomotive. (3) Figure 2(c) shows that the leading locomotive sends an electronically controlled ECP signal, and the slave control locomotive sends an electro-pneumatic signal forward and backward simultaneously after receiving the signal from the leading locomotive. It should be noted that the segmented electro-pneumatic brake has the characteristics of co-propagation of air brake signal and electric brake signal. The above three kinds of slave control locomotives have the ability to send air brake signals to both sides of the locomotive. According to whether the slave control locomotive sends the electronically controlled ECP signal, and the way the slave control locomotive sends electronically controlled ECP signal after receiving the electrical signal send by the leading control locomotive, the above three kinds of electronically controlled ECP signal propagation methods are referred to as “not sent, send backwards, send forwards and backwards”.

The analysis of three propagation modes of electro-pneumatic ECP signal

The problem that needs to be solved in the operation of long heavy-haul trains is to reduce the longitudinal impulse and braking distance when the train is running. Selecting the appropriate braking signal propagation mode is beneficial to improve the braking characteristics of the train, thereby reducing the longitudinal impact and braking distance. For this reason, this section studies the longitudinal impulse level and train braking ability of three ECP electronic control signal propagation modes of segmented electro-pneumatic braking for 30,000-ton heavy-haul trains.

The locomotive in the simulation model of 30,000-ton heavy haul train is HXD1 electric locomotive, and the vehicle is C80 freight vehicle, two vehicles in a set of traction rods. The draft gear type is MT-2. The initial braking speed is 70 km/h, and the electro-pneumatic braking mode is adopted. The action mode of electro-pneumatic brake is sequential action, and the wave velocity of electrical signal propagation is 1000 m/s, and the simulation condition is straight line. The test of 20,000-ton heavy-haul train shows that in general, the difference between the starting time of the slave control locomotive and the leading locomotive is about 2∼3 s, and even reaches 5∼6 s in extreme cases, so this paper chooses the slave control locomotive to lag behind the leading locomotive for 2 s as an example.

Comparison of coupler forces under braking conditions

When the train brakes, the response of each vehicle is unsynchronized. The vehicle close to the locomotive brakes first, and the speed decreases faster than the rear vehicle, which causes the rear vehicle to rush forward and makes the front coupler in a compressed state. When the speed of the front rear vehicle is reduced to approach, the whole train is in the maximum compression state, resulting in the maximum coupler compressing force, so the coupler compressing force of the train is analyzed under braking conditions.

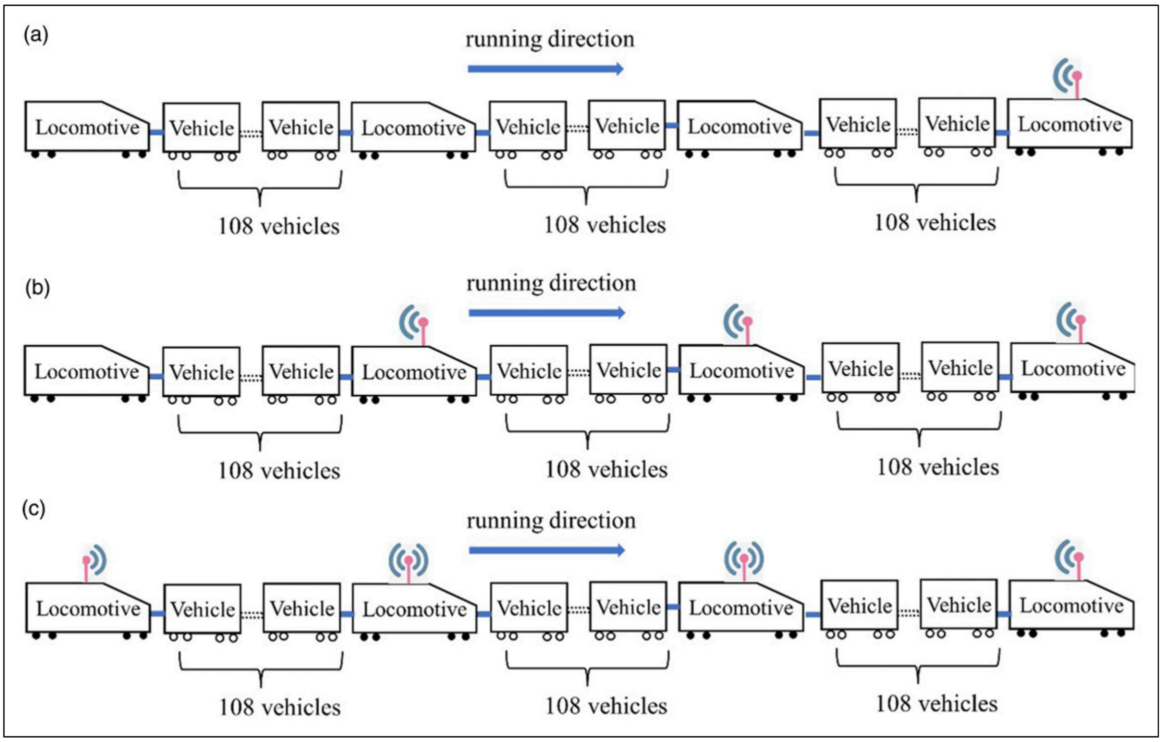

Figure 2. 30,000-ton heavy-haul train and three ECP electro-pneumatic signal propagation modes. (a) not sent, (b) send backwards, (c) send forwards and backwards.

Figure 3 shows the distribution curves of the maximum coupler force along the length of the train when braking with a reduction of 100 kPa and emergency braking on the straight road. The results show that the maximum coupler force generated by the three ECP signal propagation modes has the same distribution trend along the length of the train, and the coupler force at the front and rear of the train is small during braking, while the coupler force is large in the range of vehicle serial number 200–250. With the service braking for a 100 kPa reduction, the maximum coupler force produced by "not sent" propagation mode is 872.3 kN, which is located in the 238th vehicle. "Send backwards" corresponds to the maximum coupler force of 696.2 kN, which is located in the 218th vehicle. "Send forwards and backwards", the maximum coupler force is 560.3 kN, which is located in the 252nd vehicle, and the maximum coupler force is reduced by 35.8% and 19.5% respectively compared with the previous two modes. During emergency braking, the maximum coupler force of "send forwards and backwards" is reduced by 10.5% and 5.2% respectively compared with the former two. That is to say, the maximum coupler force produced by the ECP signal propagation mode of "send forwards and backwards" is the smallest compared with the other two propagation modes.

Comparison of braking distances

Table 1 shows the train running at an initial speed of 70 km/h, and the braking distances of three ECP electronic control signal propagation modes in service braking conditions for reduction of 50 kPa, 100 kPa, 170 kPa and emergency braking. It can be seen from the braking distance of the four pressure reduction that the ECP electronic control signal propagation mode has little effect on the braking distance. However, compared with the other two methods, "send forwards and backwards" has the shortest braking distance under the same pressure reduction, and "not sent" is the longest. When at 50 kPa, 100 kPa and 170 kPa of pressure reduction, the parking distance of "send forwards and backwards" is reduced by 0.4%, 0.5% and 1.2% respectively compared with "not sent". During emergency braking, compared with "not sent", "send forwards and backwards" decreased by 1.2%, with little change.

Influence of lag time of slave control locomotive on three ECP electronic control signal propagation modes

The coupler force of heavy-haul train is closely related to the characteristics of braking system. The slave control locomotives located at different positions in the train are the source of braking signals, and these signal sources have different lag time with the leading locomotive. Therefore, it is very difficult to obtain the braking characteristics of the slave control locomotive and the leading locomotive with any lag time through a small number of tests. In addition, the difference of braking pressure reduction between train tail locomotive and leading locomotive, it will become more difficult to obtain this kind of train braking characteristics. Inaccurate braking characteristics will bring more unreliability to the coupler force prediction, so how to obtain the braking characteristics corresponding to different ECP signal propagation modes of 30,000-ton heavy-haul trains is a significant problem. Therefore, this section studies the influence of lag time on the propagation characteristics, longitudinal pulse level and braking ability of the three propagation modes of the ECP electronic control signal of the segmented electro-pneumatic brake through the simulation system. Among

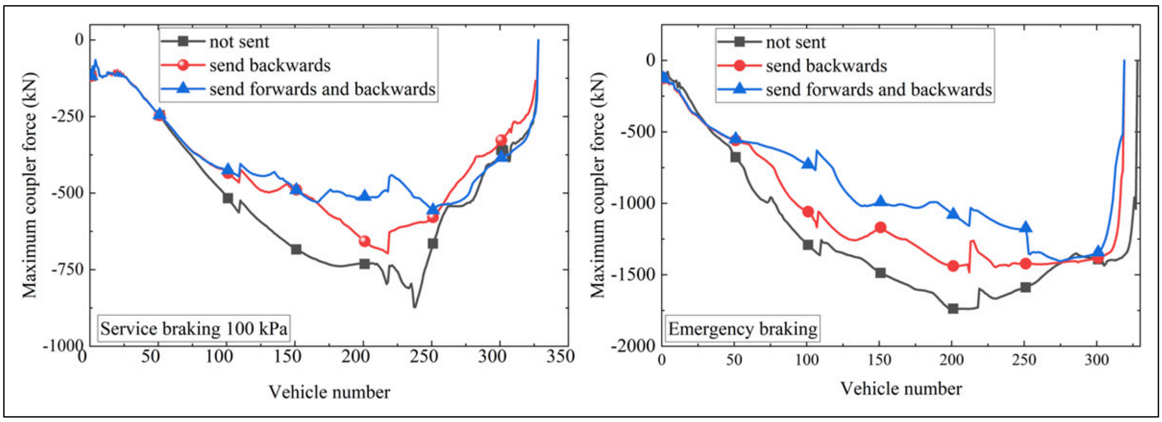

Figure 3. Distribution of maximum coupler force along vehicle length under braking conditions.

Table 1. Braking distance of three propagation modes under different braking conditions.

Pressure reduction	Not sent braking distance/m	Send backwards braking distance/m	Send forwards and backwards braking distance/m
50 kPa	2588.4	2591.6	2578.0
100 kPa	916.0	912.8	911.5
170 kPa	702.9	699.2	696.9
Emergency braking	492.4	489.1	486.6

the two ways in which slave control locomotives have the ability to transmit ECP signals, the relationship between whether slave control locomotives can effectively transmit ECP signals and the lag time of leading-slave locomotives is discussed.

Influence of lag time on coupler force

Taking the 100 kPa reduction as an example. Figure 4 shows the coupler force distribution along the train length corresponding to the above three ECP signal propagation modes under different lag time of the slave control locomotive. As can be seen from the figure, with the increase of the lag time of the slave control locomotive, the maximum coupler force generated during train braking increases. When the lag time is 0~3 s, the maximum coupler force of "send forwards and backwards" is reduced by 50.8%, 37.1% and 6.7% respectively compared with that of "not sent". "Send backwards" is 38.6%, 17.8% and 0.01% lower than "not sent" respectively. When the lag time is 0 s and 1 s, the coupler forces of "send forwards and backwards" and "send backwards" are obviously reduced compared with "not sent". But with the increase of the lag time, the three curves will gradually approach, and when the lag time is 3 s, the coupler forces corresponding to "send backwards" and "not sent" basically coincide along the vehicle length distribution curve. That is to say, with the increase of the time of the slave locomotive lagging behind the leading locomotive, the relative variation of maximum coupler force corresponding to different ECP electronic control signal propagation modes decrease.

Influence of lag time on braking distance

Figure 5 shows the braking distances corresponding to three ECP electronic control signal propagation modes when the train is in emergency braking and backing with a reduction of 100kPa. The calculation range of the lag time of the slave control locomotive is 0–3 s. When at 100 kPa of pressure reduction, the braking distance of"send forwards and backwards"is reduced by 3.0%, 1.5%, 0.5% and 0.04% respectively compared with "not sent". During emergency braking, "send forwards and backwards" is 4.8%, 2.7%, 1.2% and 0.2% lower than the former. With the increase of the lag time of the slave control locomotive, the difference of train braking distance corresponding to different ECP electronic control signals decreases.

Influence of lag time on the propagation law of brake wave

The segmented electro-pneumatic brake system is characterized by the co-propagation of electrical signals and air signals. However, the propagation of these signals alone is not enough to fully represent the braking law of each vehicle in the train. Therefore, it is more appropriate to represent the propagation characteristics of train braking wave by the extension time of brake cylinder piston. The extension time of the brake cylinder piston represents the time when the brake wave propagates to the vehicle. The extension time curve of the brake cylinder piston is also the brake propagation characteristic curve. Figure 6 shows the braking cylinder piston extension time corresponding to

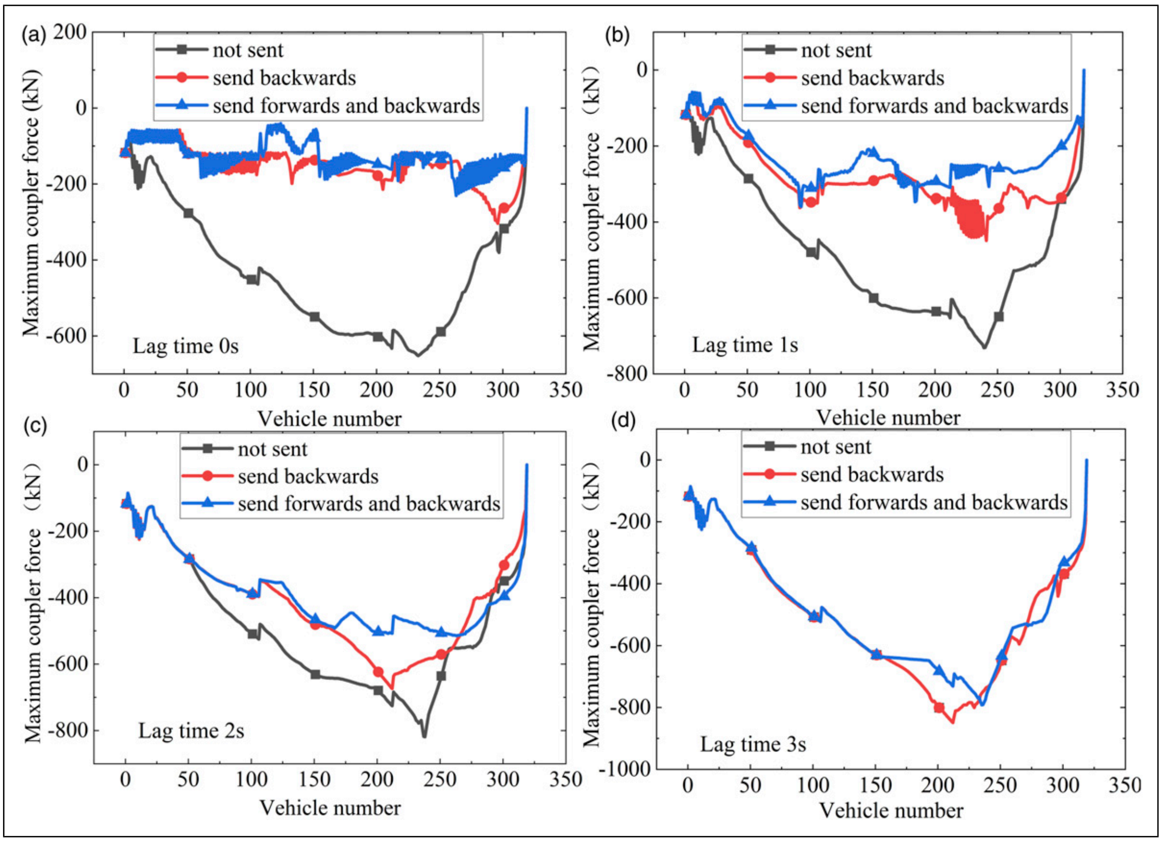

Figure 4. Distribution of coupler force along vehicle length with different lag time.

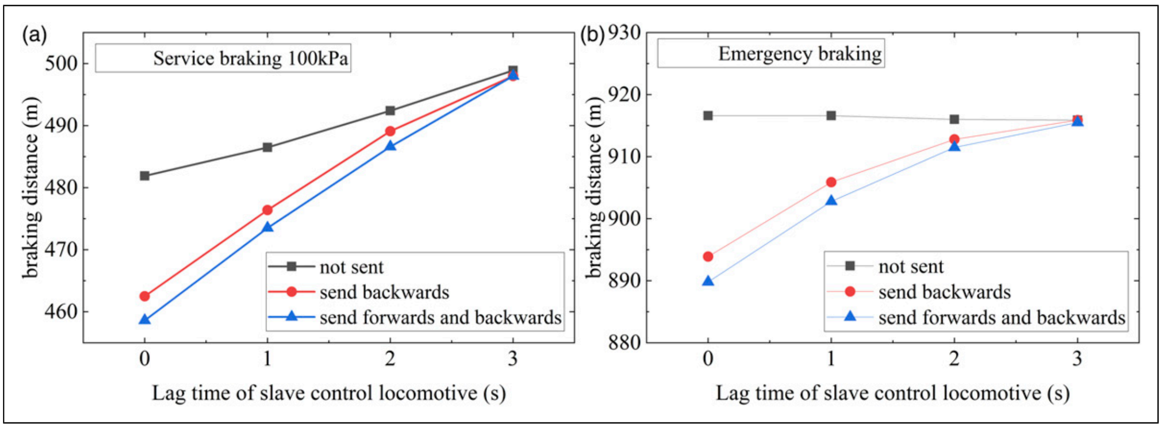

Figure 5. Braking distance corresponding to different lag time.

three kinds of ECP electronic control signals, that is, the braking wave propagation characteristics, for slave control locomotives with different lag times. Time = 0 s is the time when the simulation starts, not the time when the train starts to brake. The braking time of the train is 22.7 s, that is, the extension time of the brake cylinder piston corresponding to the first vehicle behind the leading control locomotive is 22.7 s. The main purpose of braking after 22.7 s of train operation is to simulate the braking condition when the train is running normally.

With the increase of the lag time of the slave control locomotive, the curves of the piston extension time of the vehicle brake cylinder corresponding to the three ECP electronic control propagation modes are gradually approaching, and the difference between the latest and earliest piston extension time of the corresponding vehicle brake cylinder is reduced. This is also the reason why the maximum coupler force and braking distance corresponding to the three modes decrease with the increase of lag time. It can be seen that whether the slave control locomotive can effectively exert its ability to send ECP signals is closely related to the lag time of the leading and slave control locomotives. The longer the lag time, the less the number of slave control locomotives can play the role of propagating ECP signals.

Taking the lag time 2 s of the slave control locomotive as an example, as shown in Figure 6(c). For "not sent", after the vehicle near the rear slave control locomotive (The third slave control locomotive) receives the remote control signal of the leading locomotive, the brake pipe begins to exhaust. This reduction process transmits the air brake signal forward. The ECP electric control signal of the rear vehicle of the 30,000-ton train arrives late, which is quite different from the time when the rear locomotive begins to receive the locomotive remote control signal (the lag time of the slave control locomotive is 2 s), so the rear locomotive has a long air braking propagation time. From the simulation results, the exhaust of the slave control locomotive 1 and 2 has little effect on the propagation of the air brake wave. For "send backwards", after the exhaust of the second and third slave control locomotives, although the front part of the vehicle is affected by the air brake wave, the number of affected vehicles is significantly less than that of "not sent". For "send forwards and backwards", the braking wave propagation caused by air braking has little effect. Only by a small fluctuation in the curve near slave control locomotive 1 and 2 can a small effect be seen.

By comparing the latest and earliest action vehicle brake cylinder piston extension time difference, we can qualitatively evaluate the three ECP signal propagation modes. For "not sent", the time is 3.6 s; the differences between "send backwards" and "send forwards and backwards" are 3 s and 2.6 s, which are 16.7% and 22.8% lower than "not sent", respectively. These findings suggest that the "send forwards and backwards" propagation mode allows for a quicker start time of the brake cylinder piston extension and minimizes the time delay in vehicle braking compared to the other two propagation modes.

Simulation results of long ramp

China's Shuohuang railway line from the west of Shanxi Shenchi County, east to Huanghuagang City, Hebei Province. Taking Shenchi South as the coordinate origin of the whole line 0 m. The Nanwan-Xiaojue section is one of the sections of the line. It is a continuous long downhill slope of 10~12‰, which is a difficult road to pass. The main features are that the bridge and tunnel are connected, the altitude drop is large, the curve radius is small, and the line is extremely complex. The main idea of this chapter is to simulate the operation of 30,000 tons of heavy haul trains using air braking and segmented electro-pneumatic braking respectively on the line to ensure that the train passes the line normally. The advantages and disadvantages of the two braking modes are analyzed by comparing the coupler force. By comparing the position of starting braking and relieving, it provides a reference for the operation method of segmented electro-pneumatic braking on long ramp in the future.

Simulate the cyclic braking operation of 30,000-ton heavy-haul train with air braking and segmented electro-pneumatic braking respectively, to ensure that the train has the same speed when braking and relieving each time, and compare the differences of cyclic braking operation. The signal propagation type of segmented electronic control ECP is "send forwards and backwards". The initial position of the leading locomotive is set at k143 + 500 m in the section from Nanwan to Xiaojue District on the Shuohuang Line. Figure 7 shows the normal operation instruction and

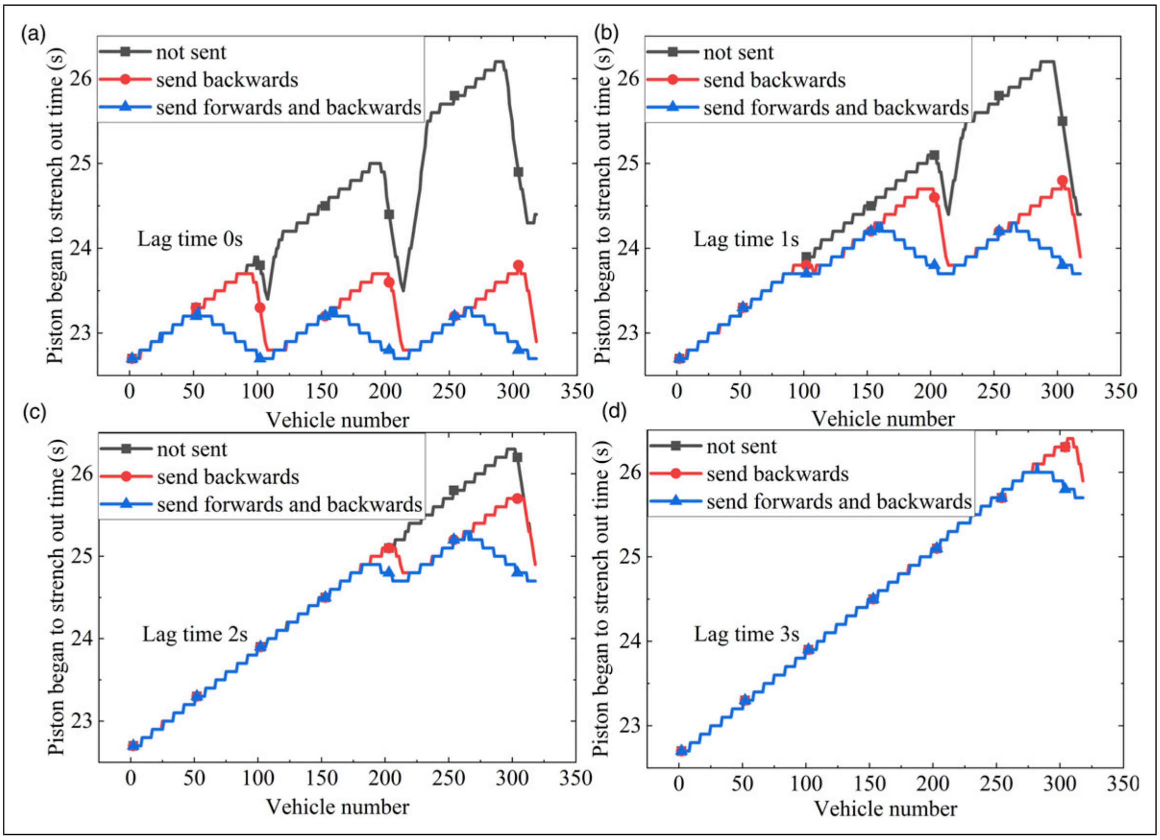

Figure 6. Propagation characteristics of braking wave corresponding to three ECP electronic control signal propagation modes with different lag time.

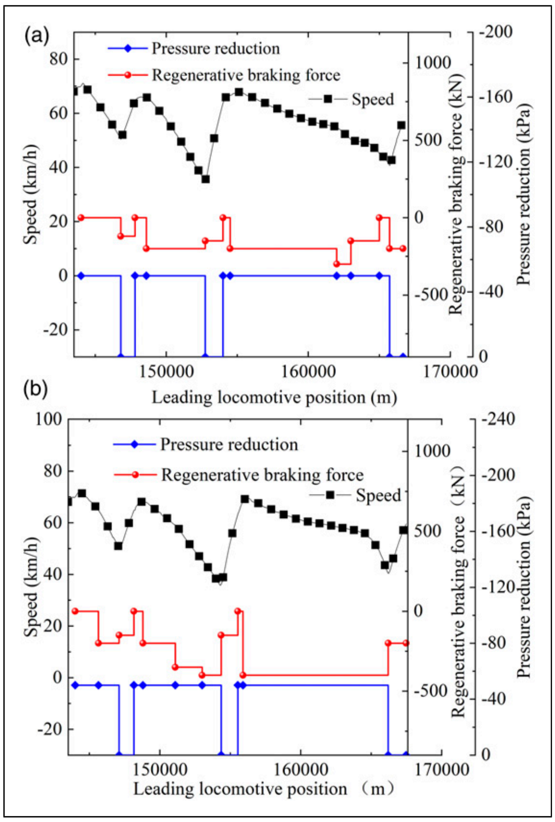

Figure 7. Long ramp-normal operation instruction and train speed curve. (a) Segmented electro-pneumatic braking, (b) Air braking.

train speed curve of the train using segmented electro-pneumatic braking and air braking respectively. A total of three brakes are used, and the braking and releasing position and starting braking and releasing speed of each brake meet the control requirements.

The actual operation requirements of the line are as follows:

First cycle braking

At k144 + 000 m, the train speed is guaranteed to be 70 km/h, and the train is braked with a reduction of 50 kPa. At k145 + 500 m−k147 + 300 m, the train speed is controlled to be no less than 50 km/h to start the relief, and the regenerative force of 200–300 kN can be applied to the relief train.

Second cycle braking

After the release, to ensure that the train speed does not exceed 65 km/h, the service braking conditions for reductions of 50 kPa is applied. Before k156 + 500 m, the train speed is controlled in the range of 35–40 km/h, and the regenerative force 200–300 kN is used to alleviate the train.

Third cycle braking

Ensure that the train air filling time and train speed does not exceed 68 km/h, the service braking conditions for reductions of 50 kPa is applied. After the slave control

Table 2. The position and time of train starting braking and relieving.

	Cyclic braking	Start braking position/m	Start braking time/s	Start relief position/m	Start relief time/s
Segmented electro-pneumatic braking	1	k144 + 000	26	k146 + 800	190.8
	2	k147 + 800	254	k152 + 750	596.1
	3	k154 + 000	689	k165 + 720	1419.3
Air braking	1	k144 + 000	26	k147 + 110	203.5
	2	k148 + 160	286.6	k154 + 260	685.9
	3	k155 + 530	772.7	k166 + 200	1426.5

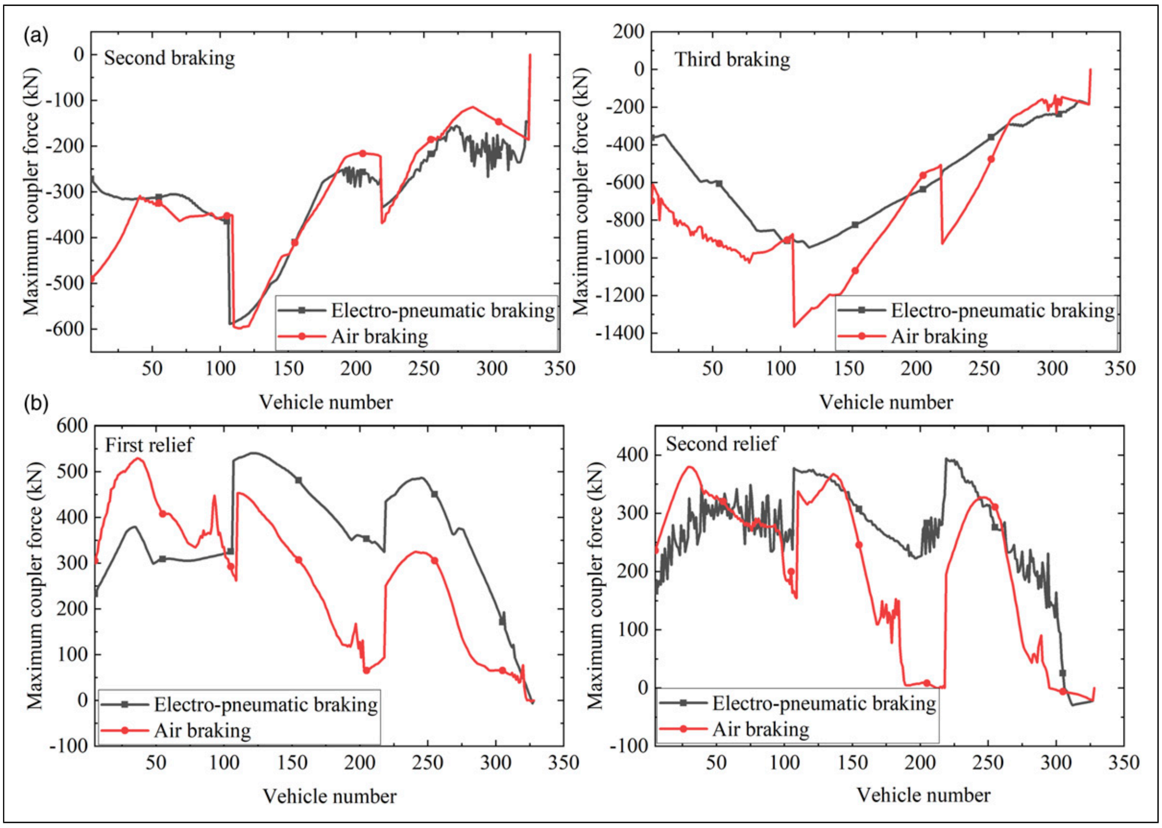

Figure 8. Maximum coupler force distribution along the vehicle length. (a) Braking condition, (b) Relieving condition.

locomotive passes through the phase, that is, k165 + 700 m−k166 + 400 m, the train speed should be controlled in the range of 35–55 km/h, and the regenerative force of 200–300 kN should be applied to alleviate the train.

Each time the train brakes and relieves the position, it has undergone repeated experimental tests. The use of a modified operation method can ensure that the train is safely out of the line.

In Figure 7, the x-axis represents the position of the leading control locomotive in the entire Shuohuang line. The simulation starts at k143 + 500 m and ends at k166 + 675 m (the position of Shenchi South is the coordinate origin of the x-axis). The left Y-axis represents the speed of the leading control locomotive, and the right two Y-axis represent the regenerative braking force (The regenerative force of the four locomotives is the same. The figure is the regenerative braking force of a locomotive. The regenerative braking force of the whole train should be multiplied by 4.) and the pressure reduction.

Taking segmented electro-pneumatic braking as an example, this paper introduces the simulation operation method of cyclic braking of 30,000 t train. Set the initial speed of the train to 68 km/h, and the train will run normally for 500 m until it reaches the braking position of the first brake. At this time, the train speed is 70.09 km/h, which is very close to the 70 km/h required by the operation method and meets the operation requirements. At this time, the train will be braked by the service brake reduction of 50 kPa. After 164.8 s, the train arrived at k146 + 800 m, and applied regenerative force of 120 kN to relieve it. At this time, the train speed was 50.45 km/h, and the relieving speed was not less than 50 km/h to meet the operation requirements. The release time of the first brake is 64 s. During this period, the train speed reaches 64.58 km/h, which meets the operating requirements below 65 km/h, and the second brake is started. In order to make the train meet the relief speed requirements at k148 + 600~152 + 670 m, an additional regenerative braking force of 200 kN is applied to brake the train. After 435 s, the train traveled 4950 m to k154 + 000 m, and the second braking ended. The train is relieved under the action of regenerative force of 150 kN. After 101s of relief, the train travels 1250 m to k154 + 000 m and starts the third braking. At k154 + 500 m, 200 kN regenerative braking force is applied. At k162 + 000 m, 300 kN electric braking force is applied. At k163 + 000 m, 150 kN regenerative braking force is applied. After 747 s, the train traveled 12,970 m to k165 + 720 m, and the 200 kN regenerative braking force was used to relieve the train.

Differences in manipulation

Compared with air braking, segmented electro-pneumatic braking on trains requires less regenerative braking force, and the number of changes of regenerative brake handle is reduced, which simplifies the driver's operation mode.

Table 2 shows the position and time of the train starting braking and relieving corresponding to the two braking modes. Comparing the segmented electro-pneumatic braking with air braking, the three braking positions are 0 m, 360 m and 1530 m earlier respectively. The positions of the three reliefs are advanced by 310 m, 1510 m and 480 m respectively. In terms of time, compared with air braking, when using electro-pneumatic braking, the braking time can be 0 s, 32.6 s and 83.7 s later, and the starting time of relief can be delayed by 12.7 s, 89.8 s and 16.9 s s. In addition, the time required for segmented electro-pneumatic braking during braking is short.

Comparison of coupler force

Figure 8(a) is the distribution curve of the maximum coupler force along the vehicle length corresponding to the two braking modes in the last two times. In the braking condition, the pressure hook force is mainly analyzed. The maximum coupler forces generated by the train using air brake in the two braking processes are 598.1 kN and 1366.7 kN, respectively, located in the 107th and 110th vehicles. The maximum coupler forces corresponding to electro-pneumatic braking are 588.6 kN and 944.7 kN, which are located in the 107th and 121st vehicles, which are 1.6% and 30.1% lower than the former.

Figure 8(b) shows the distribution curve of the maximum coupler force along the length of the vehicle corresponding to the two braking modes in the process of two releases. In the relief condition, the coupler tension is mainly analyzed. There is little difference in the maximum coupler force produced by the two braking methods in the relieving working condition. The maximum coupler forces corresponding to two times of air braking are 394.3 kN and 529.2 kN, which are located in the 31st and 36th vehicles. The maximum coupler forces corresponding to electro-pneumatic braking are 379.4 kN and 540.4 kN, which are located in the 219th and 123rd vehicles. Compared with the former, the first release is reduced by 3.9% and the second release is increased by 2.1%.

Conclusions

1. Three propagation modes of segmented electrical braking ECP signal are proposed, which have the characteristics of co-propagation of electrical signal and air signal. A 30,000-ton heavy-haul train model is established in TABLDSS simulation system, and the propagation characteristics, train braking ability and longitudinal impulse level of three ECP electronic control signal propagation modes of segmented electro-pneumatic braking are compared. The results show that the signal propagation mode is the best when the leading locomotive is backward and the ECP signal is propagated from the slave control locomotive forward and backward. Compared with the worst case that only the leading locomotive sends the ECP signal backward, the coupler force can be reduced by 46.5%, the time difference between the slowest and fastest vehicles can be reduced by 60.5%, and the emergency braking distance can be reduced by 1.2%. Therefore, it is suggested that the 30,000-ton train adopt the mode that the leading locomotive sends ECP signals while the slave control locomotive sends ECP signals forward and backward.
2. The influence of the slave control locomotive's lag in the time of the leading locomotive on three ECP electronic control signal propagation modes is analyzed. The results show that, among the two ways in which the slave control locomotive has the ability to send ECP signals, whether the slave control locomotive can effectively play its role in sending ECP signals is closely related to the position of the slave control locomotive and the lag time of the leading and slave control locomotive. The shorter the lag time of leading and slave control locomotives, the more slave control locomotives can play their role in propagating ECP signals.
3. Take the existing line of Nanwan - Xiaojue District of the Shuohuang Line, as an example, which is located on a long and steep downhill, to simulate the cyclic braking operation of 30,000-ton heavy-haul trains using air braking and segmented electro-pneumatic braking, and compare the differences between the two braking modes in the cyclic braking operation on a long ramp. The results show that compared with air braking, the two starting braking time of the train can be delayed by 32.6s and 83.7s respectively, and the three relieving time can be delayed by 12.7s, 89.8s and 16.9s respectively. The electric braking force and regenerative force used are small, and the action time is short, which can simplify the driver's operation. In addition, the maximum coupler force can be reduced by 30.1%.

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