Minimum Safety Distance Model Based Follow Operation Control of High-speed Train

Haiying Dong, Xirui Gao, Zhigang Luo, Feng Chang

Abstract—**The operation of the high-speed railway has the requirements of safety, efficiency and comfort. Based on the original model of the safety distance between running trains, a new minimum safety distance model representing the following state of the high-speed train, which incorporates the real-time speed of the preceding train, is given. This model takes the braking of the preceding/following train in the most favorable/unfavorable conditions into account. As a criterion for behavioral adjustment of the following train, algorithms for the principle of velocity-difference control is proposed on the basis of the real-time tracking of the dynamic safety following distance. By applying the algorithms, the following train can adjust itself to the behavioral adjustment of the preceding train in a safe and efficient following state. Simulation is carried out by taking the basic data of the CRH5G and parameters of actual line. The results show that the actual following distance can be controlled commendably by the behavioral adjustment of the following train. The new minimum safety distance model is effective in shortening the safe headway and enlarging the passing capacity.**

Index Terms—**safety distance, high-speed train, safe and efficient, following state**

I. INTRODUCTION

High-speed train has the characteristics like large capacity, fast velocity, safety, punctuality, etc., which make it become an important part of the railway transportation system. The vehicle-following control problem is to track errors (velocity error and distance error) of the preceding and the following vehicles. The road condition, the operation state of the vehicle, the related dynamic information and the control commands of the vehicle are essential for achieving a safe and efficient traffic target.

The vehicle-following theory is an important part in traffic flow simulation and is characterized by the driving behavior of drivers in real life and the detailed characteristics of vehicle operation [1]. Since the early 1960s, studies of vehicle following theory have been classified into 5 types, namely the GHR (Gazis-Herman-Rothery) model, the safety distance model, the linear model, the psychological model and the fuzzy theory based model [2]. These models attempt to restore the real process of vehicle-following to the greatest extent from different aspects, such as the minimum velocity difference [3-4], the optimal following velocity [5], the safe following distance [6], and the track repetition [7]. Among them, the vehicle-following model in traffic flow theory has attracted more and more attentions. It has been widely used in studying the evolution of the traffic flow under different sceneries. Abovementioned achievements are mainly used in the field of highway transportation, but seldom applied in rail transit. In fact, the car following theory is more suitable for simulating the rail transit as the role of the vehicle in the rail transit system is one-way, and it satisfies the assumptions of car following theory [8], each driver only needs to respond to the incentives from the preceding train. Above methods provide references for the study of the following operation control of the high-speed train.

With the rapid development of the high-speed railway, the railway transportation department has been improving the efficiency and safety requirement. More and more attentions have been paid on the following operation and control of the train [9-16]. Y. Fu *et al* [9] applied cellular automation for modeling and simulation of the train following operation to study the regularity of operation of the train. By considering the operation control mechanism of the high-speed train and evaluating the following operation quality of the train at high velocity, D. Pan *et al* [10-11] provided the basis for the control of the train. By defining the so-called Lagrange multipliers and solving the optimization equations, A. Albrecht *et al* [12] proposed an optimal control strategy of the following train that influenced by the following train with analyzing the following operation process of two trains. For the purpose of energy saving, J. Ye *et al* [13] proposed an optimized velocity-following model and verified its effectiveness by using measured data. W. Shang *et al* [14] proposed a method for calculating the curve of the high-speed train in breaking mode when its velocity is higher than 250 km/h. Considering the punctuality, energy conservation, comfortability and other performance in the operation of the train, Y. Lin [15] designed a method for on-line auto train operation (ATO) curve calculation. According to the use target and the maximum allowable velocity of the train, L. Luo *et al* [16] calculated the safety interval of the moving block system of the train in urban rail transit system.

Abovementioned results have laid good foundations for further study since the development of the high-speed train is stepping into a new period with higher speed and better

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Haiying Dong is with the School of Automation and Electrical Engineering, Lanzhou Jiaotong University, No. 88, Anning West Road, Lanzhou, P.R. China (Tel: 86-13893669428; e-mail: hydong@mail.lzjtu.cn).

Xirui Gao is with the School of Automation and Electrical Engineering, Lanzhou Jiaotong University, No. 88 Anning West Road, Lanzhou, Gansu, P.R. China (e-mail: gaoxirui_vip@163.com).

Zhigang Luo is with the China Railway Shanghai Design Institute Group Co. Ltd., No. 291, Tianmu Middle Road, Shanghai, P.R. China (e-mail: 448273661@qq.com).

performance. The successful application of the moving block can not only reduce the fixed equipment investment of both the line and the station, but also shorten the minimum interval of the trains more effectively. With the application of the moving block system, it is achievable to make the goal of high density and high velocity operation of the train come true and the capacity of the operation line improved. In time adjustment of the specific behaviors of the train according to the dynamic change of train operation can be helpful for improving the quality of the operation control of the train and the efficiency of railway transportation.

Generally, the velocity and the distance between two high-speed trains vary dynamically during the process of following operation. The trains need to adjust their behavior according to the traffic conditions, the operation state and operation control commands. This paper first analyzes the real-time model for minimum safety distance calculation of the high-speed train, and discusses its adjustment strategy based on the principle of vehicle-following operation control. It then designs and proposes the control principle of safe, efficient and comfortable operation for the high-speed train. Simulation results finally validate the effectiveness of the proposed method in studying of the following control of the high-speed train. The proposed method is an attempt and exploration for the future research of the train operation control system of CTCS-4.

II. REAL-TIME MODEL FOR MINIMUM SAFETY DISTANCE CALCULATION OF THE TRAIN

A. Traditional safety following distance model of the train

At present, the safety following distance model of the moving block train is established based on the automatic train protection (ATP) safety braking curve according to IEEE 1474.1 [17], as shown in Figure 1.

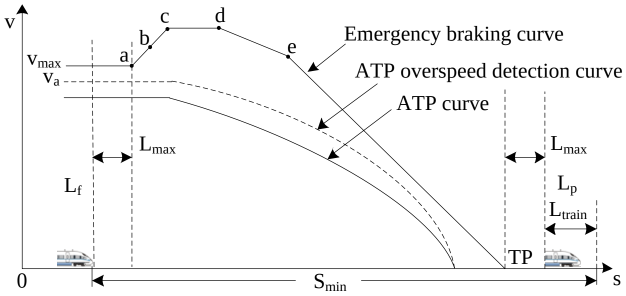

Fig.1 Safety distance model

In Figure 1, the ATP safety braking curve is generated according to both the safety and high efficiency requirements of the train. The ATP safety braking curve incorporates the following three types of data: 1) information relating to the self-performance of the train (i.e. parameters of the braking performance of the train), 2) line information (i.e. line velocity, line slope and curvature), 3) the limit of movement authority (LMA), the information of mobile authorized location and the temporary limiting-speed [18].

Under the most unfavorable condition during braking, the train's minimum safety following distance that controlled by existing algorithm can keep the train stop within the LMA protected area, and ensure the operation safety. The position of the following train's LMA is just located in point TP in Figure 1, and its equation can be expressed as:

$$S_{\mathrm{LMA}} = L_{TP} = L_p - L_{\mathrm{train}} - L_{\max} \tag{1}$$

where L_p is the detected position of the preceding train, $L_{\max}$ is the maximum error of the detected position, and L_{trian} is the length of the train.

The most unfavorable conditions during the braking of the following train include:

(1) The position error of the preceding and the following trains detected by speed sensor is the highest.

(2) When the train is overspeed, it accelerates with the maximum traction, as shown in line *a-b-c* in Figure 1,.

(3) Time delay of the system is maximum.

(4) The braking system of the train fails to export brake force due to malfunction. Baking is actualized by the guaranteed emergency brake rate (GEBR, equivalent to the minimum emergency braking rate).

(5) The line is unconducive to realize braking of train, such as large ramp, etc..

In view of the abovementioned unfavorable conditions during the braking of the train in traditional model, as shown in Figure 1, parameters of the existing model in terms of the safety distance are given below:

(1) The equation for calculating the position of the tail of the preceding train,

$$S_p = L_p - L_{\mathrm{train}} - L_{\max} \tag{2}$$

and the equation for calculating the location S_f and the velocity v_f of the following train:

$$\begin{cases} S_f = L_f + L_{\max} \\ v_f = v_a + v_{\max} \end{cases} \tag{3}$$

where L_f is the detected position of the following train, v_a is the allowable velocity of the ATP safe braking curve, and $v_{\max}$ is the maximum error of the calculated velocity of the on-board equipment.

(2) Overspeed time t_{ac} of the train with the maximum traction before touching the ATP safe braking curve, as shown in Figure 1:

$$t_{ac} = t_{ab} + t_{bc} \tag{4}$$

where t_{ab} is the time required for the ATP safety brake curve to detect the overspeed of the train, t_{bc} is the required time for stopping the traction after the train is overspeed.

(3) Coasting time t_{ce} of the train, referring to line *c-d-e* in Figure 1:

$$t_{ce} = t_{cd} + t_{de} \tag{5}$$

where t_{de} is the time required for brake set up of the train's control equipment, and t_{cd} is the time for control equipment to remove the traction and prepare to start braking.

(4) After braking with GEBR, the train continued running for t_{GEBR} till its velocity close to zero and finally stopped before the point TP (line e-TP in Figure 1).

(5) The adopted line data is the specific line data obtained by using ATP.

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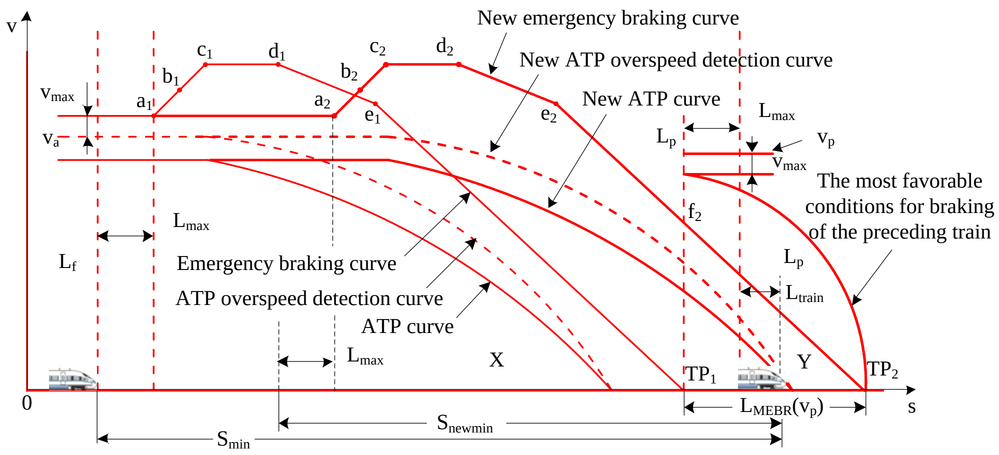

Fig.2 Improved minimum safety distance model

B. Improved minimum safety following distance model

Apart from the three kinds of data utilized in the traditional model, the velocity information and performance parameters of the preceding train is also added in the improved minimum safety following distance model. By considering the most unfavorable conditions of the following train as well as that of the preceding train for braking, an improved real-time model for minimum safety distance calculation of following operation of the high-speed train is established. The principle is shown in Figure 2

The most favorable conditions for braking of the preceding train include the following aspects:

(1) When the condition data relating to the preceding train is transmitted through wireless communication, the braking force is outputted as the maximum emergency brake rate (MEBR).

(2) The position and velocity of the preceding train are most favorable for parking brake.

(3) The preceding train can output the braking force required for braking.

(4) The line data is most favorable for braking of the preceding train, such as the upper ramp.

As is shown in Figure 2, based on the performance parameters, position and velocity information of the preceding train, the safety distance optimization algorithm of the train can predict its parking position as the following train's LMA according to the braking calculation method with the most favorable condition. Then the following train can generate ATP safe braking curve according to braking calculation method with the most unfavorable condition to ensure the safety operation of the train.

The LMA equation of the following train in the improved minimum safety distance algorithm is:

$$S_{new} = L_{TP_2} = L_p - L_{\text{train}} - L_{\max} + L_{\text{MEBR}}(v_p) \tag{6}$$

where, $L_{\text{MEBR}}(v_p)$ is the moving distance of the preceding trains at the speed of v_p according to the most favorable braking condition. The MEBR is the maximum braking rate the train can output.

Compared with the results obtained from the traditional algorithm in (1) and (6), we can obtain:

$$L_{TP_2} > L_{TP_1} \tag{7}$$

It is clear that the LMA of the following train in (7) in the improved algorithm is longer than that in the traditional algorithm. The following train is influenced by the preceding train and moved forward from point a_1 to point a_2 as shown in Figure 2.

The specific algorithm of the most favorable condition for braking of the preceding train is given as follows:

(1) The system response and information transfer delay are assumed to be equivalent to zero.

(2) The line data adopted here is obtained by using ATP specifically.

(3) The preceding train can has the ability to output required braking force normally at the speed of v_p, and it should be calculated by the maximum braking force B_{MEBR} outputted by MEBR at the ideal condition.

(4) Equation (3) is adopted for calculating the position and the velocity of the following train.

(5) The velocity and position of the preceding train are most favorable for braking. The tail position S_p and velocity v_p of the preceding train can be expressed as:

$$\begin{cases} S_p = L_p - L_{\text{train}} - L_{\max} \\ v_p = v_{\det} - v_{\max} \end{cases} \tag{8}$$

where $v_{\det}$ is the velocity detected by on-board equipment.

As a result, the safety distance S_{safe} between the preceding and following trains can be retained:

$$S_{safe} = S_{new} = L_p - L_{\text{train}} - L_{\max} + L_{\text{MEBR}}(v_p) \tag{9}$$

where L_p is the location of the preceding train, $L_{\max}$ is the detected maximum location error, L_{train} is the length of the train, $L_{\text{MEBR}}(v_p)$ is the moving distance of preceding trains at the velocity of v_p under the most favorable braking condition.

III. DESIGN OF THE CONTROL SYSTEM FOR THE FOLLOWING TRAIN ADJUSTMENT

A. Calculation of the control law

At present, the train's operation control often adopts the law of "distance-to-go", regardless of the quasi-moving block system (operation control system CTCS-3 of the train) or the moving block system (operation control system CTCS-4 of the train). When the actual distance is longer than the specified target distance, the train travels at the specified velocity, while the actual distance is equal to or short than the target distance, the train decelerates with a continuous braking curve until the actual distance is longer than the specified distance. Then the train can travel with the specified velocity.

The "distance-to-go" control method considers both the safety and efficiency of the operation control of the train , it is a significant improvement of the hierarchical velocity control method that has been widely adopted by the fixed block system. In the model, the target velocity can be taken as the basis for train operation control in the safety distance model. However, the "distance-to-go" control method can only calculate the velocity-target distance by combining several initial velocities. It is unable to realize a real-time calculation of the velocity-limited target distance under the common condition as the velocities of the preceding and the following trains are different and arbitrary in the full velocity range. Thus, it is impossible to optimize the safety and efficiency at any time during the train following process. Under the principle of "safety first" and at the expense of sacrificing the efficiency of train-following, the advantages of the quasi-moving block system and moving block system have not been fully exerted.

Therefore, it is necessary to decide whether the following train needs to brake according to the velocity of the preceding train, the control strategy and the most unfavorable condition in the train-following process. Based on the technical requirements of train-following control in the future moving block system and the safe distance of the trains, the vehicle velocity fitting function can be established using numerical fitting. This function can solve the computational problem under the common following condition and at any velocity in the full velocity range. In this way, during the process of following operation, the train can choose the appropriate safety distance calculation mode according to the specific driving conditions, such as the road condition (i.e. landslides, broken rails, etc.), driving commands (i.e. fixed parking) and the availability of reliable information of the preceding train. A safe and efficient driving can then be achieved by taking the corresponding mode during operation control.

The behavioral adjustment quality of the high-speed train can be evaluated from the aspects of safety, efficiency and comfort. The safety and efficiency are closely related to the safe distance of the train, while the comfort is related to the details of the train operation. Different control strategies are adopted in the process of variable velocity operation of the high-speed train. The safety distance between the trains can be varied since the behavior details and comfort of the train are different.

The safe train distance also plays a certain constraint role in the control strategy of the high-speed train. Under the condition of safety and high efficiency: if the velocity of the preceding and following train is the same, named as steady following state with high efficiency and safety, the following train does not need to adjust its own behavior. While the velocity of the preceding and following train is different, the development of the train distance will has the adverse effect on the state of the following train in terms of high efficiency and safety. When the actual distance is longer than the safe distance, the following train needs to adjust its own behavior, and ultimately return to the steady following state with high efficiency and safety.

The control law of the following train is based on the velocity of the preceding and following train at the time when they begin to adjust. The following adjusts the safe distance in accordance with (9), and the velocity of the preceding train at this time is then taken as the final value at the end of the adjustment.

Suppose the actual distance between the preceding and following train is S, then the time derivative (S-S_{safe}) is:

$$\frac{\mathrm{d}}{\mathrm{d}t}(S-S_{safe})=\frac{\mathrm{d}S}{\mathrm{d}t}-\frac{\mathrm{d}S_{safe}}{\mathrm{d}v_f}\times\frac{\mathrm{d}v_f}{\mathrm{d}t} \tag{10}$$

where v_f is the velocity of the following train.

If S is always equal to S_{safe}, the efficiency of safety train following will be the highest. Namely, if the following train wants to adjust itself in a safe and efficient way, it should satisfy:

$$\frac{\mathrm{d}S}{\mathrm{d}t}=\frac{\mathrm{d}S_{safe}}{\mathrm{d}v_p}\times\frac{\mathrm{d}v_p}{\mathrm{d}t} \tag{11}$$

The actual distance can be calculated based on the parameters of the trains, the curvature and the slope of the line, as:

$$S=L_p-L_f \tag{12}$$

where, L_p and L_f stand for the position of the preceding and the following train, respectively.

Since

$$\frac{\mathrm{d}S}{\mathrm{d}t}=\frac{\mathrm{d}}{\mathrm{d}t}(L_p-L_f)=v_p-v_f \tag{13}$$

We can obtain (14) by combining (9) and (11):

$$a_f=\frac{\mathrm{d}v_f}{\mathrm{d}t}=\frac{(v_p-v_f)\cdot\mathrm{d}v_p}{\mathrm{d}(L_p-L_{\mathrm{train}}-L_{\max}+L_{\mathrm{MEBR}}(v_p))} \tag{14}$$

The obtained acceleration a_f is also called the unit force, which is the control law for behavior adjustment of the following train. The traction force of the following train can be calculated according to its weight, running resistance, and other parameters of the train, etc., thus help to adjust the behavior of itself.

(1) When v_p is higher than v_f, the following train will accelerate obviously to follow the preceding train.

(2) When v_p equals to v_f , the following train will run with uniform velocity following the preceding train.

(3) When v_p is lower than v_f, the following train will decelerate until it has a uniform velocity.

B. Comfort evaluation of the control principle

TABLE I
COMFORT EVALUATION BASED ON ACCELERATION

Max(|a|)	Comfort evaluation level	Max(|a|)	Comfort evaluation level
0.1	1	0.8	8
0.2	2	0.9	9
0.3	3	1.0	10
0.4	4	1.1	11
0.5	5	1.2	12
0.6	6	1.3	13
0.7	7		

The railway transportation has its own characteristics, i.e. the high-speed train has large inertia compared with other vehicles. A sudden cardiac, acceleration or deceleration can make passengers feel uncomfortable. H. Wang [20] provides the evaluation results of a fuzzy concept of comfortability based on the acceleration of high-speed train, which is shown in Table 1.

The higher the absolute value of the acceleration, the lower the comfort the passengers feel. High acceleration can cause uncomfortable for passengers in the process of deceleration of the train. Obviously, during high-speed operation state of the train, the smooth and comfortability will be reduced if the control strategy keeps constant in the process of deceleration. It reflects the actual situation that steady comfortability is gradually highlighted when the train keeps speeding up. Comfortability is the requirement from passengers about behavioral adjustment of the high-speed train, and ride comfortability requires high-speed trains run smoothly. The evaluation criterion about the stability during the process of train behavior adjustment is laid down based on the above analysis and with reference to the international standard ISO2631 [21], which is shown in table 2.

TABLE II

RIDE COMFORT EVALUATION OF HIGH-SPEED TRAIN

Acceleration range	Degree of comfort
below 0.315	not uncomfortable
0.315~0.63	slightly uncomfortable
0.63~1.00	some uncomfortable
1.00~1.60	uncomfortable
1.60~2.50	very uncomfortable
2.50 and above	extremely uncomfortable

As a result, the comfortability condition of the following train's behavioral adjustment control principle is given:

$$\begin{cases} a_f = \dfrac{(v_p - v_f) \cdot dv_p}{d(L_p - L_{\text{train}} - L_{\max} + L_{\text{MEBR}}(v_p))} \\ |a_f| \le 1.00 \end{cases} \tag{15}$$

The velocity of ground vehicle is generally lower than 500 km/h, except the acceleration and the deceleration braking process. In the safe and efficient following state, calculation method of the control principle based on the minimum safety distance model can guarantee the stability and comfortability of the following train in other stages.

C. Block diagram of following control for high-speed train

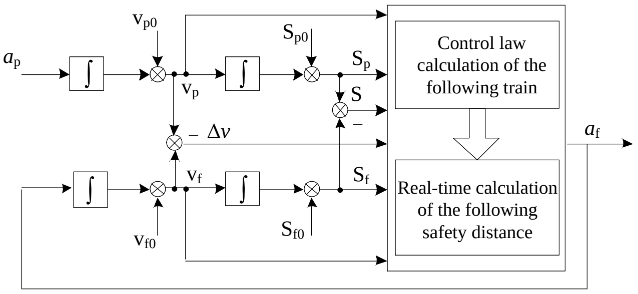

Fig.3 Diagram of train following control with high velocity.

Equation 14 is utilized to discuss the following operation control problems of the high-speed train, and the corresponding block diagram is shown in Figure 3. In the figure, a_p and a_f stand for the acceleration of the preceding and the following train, respectively. v_{p0} and v_{f0} represent the initial velocity of the preceding and the following train, S_{p0} and S_{f0} are the initial position of the preceding and the following train, respectively. Thus, we have the equation $\Delta v = v_p - v_f$ and $S = S_p - S_f$.

It can be seen from Figure 3 that the behavioral adjustment of both preceding and the following train must be realized by acceleration (unit force). The behavioral adjustment of the following train fully embodies the characteristics of the train-following process regardless of the operation state of the preceding train is changed or not. The behavior of the following train must be adjusted according to the operation state at that time even if the following train begins to adjust its own behavior in accordance with the operation condition, the dynamic information and the control command. The objective of this process is to ensure a safe and high efficient train operation.

IV. SIMULATION AND ANALYSIS

In order to verify the effectiveness of the method proposed in this paper, the EMU of the CRH5G that operated on Lanzhou-Xinjiang high-speed railway is taken as the study case. The method is verified by simulation conducted in MATLAB based on the long line data of Lanzhou-Jiayuguan section [22]. Each high-speed train has 8 carriages (5M3T), the length of the railway line is 120 km, and the schedule time is 2,130 s. The traction and braking characteristic curve of CRH5 is shown in Figure 4, and the main parameters of the train are given in Table 3.

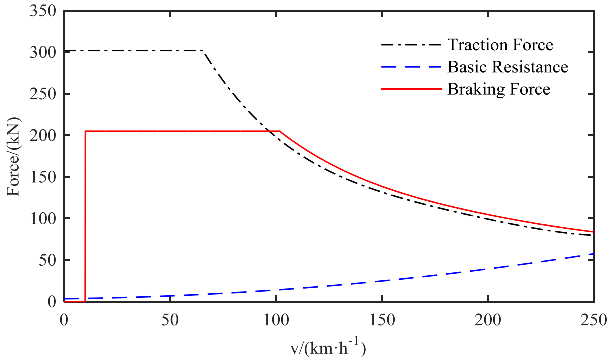

Fig.4 Traction and braking characteristic curve of the CRH5.

TABLE III

MAIN CHARACTERISTIC PARAMETERS OF TRAIN

Main parameters	Parameter characteristics
total train weight/t	80*8
train length/m	200.7
maximum speed	250
rotational mass coefficient	0.085
unit basic resistance	w_0=0.69+0.0063v+0.000146v^2

The velocity curve of the train following operation is shown in Figure 5. The preceding train has no limitations in operation except the velocity as LMA is its destination. It can operate with a maximum velocity at any positions. The following train starts from a static state in accordance with the prescribed time slot, and is affected by the preceding train in the running process. This process forms a train-following relationship between the preceding and the following train. The following train speeds up according to the adjustment

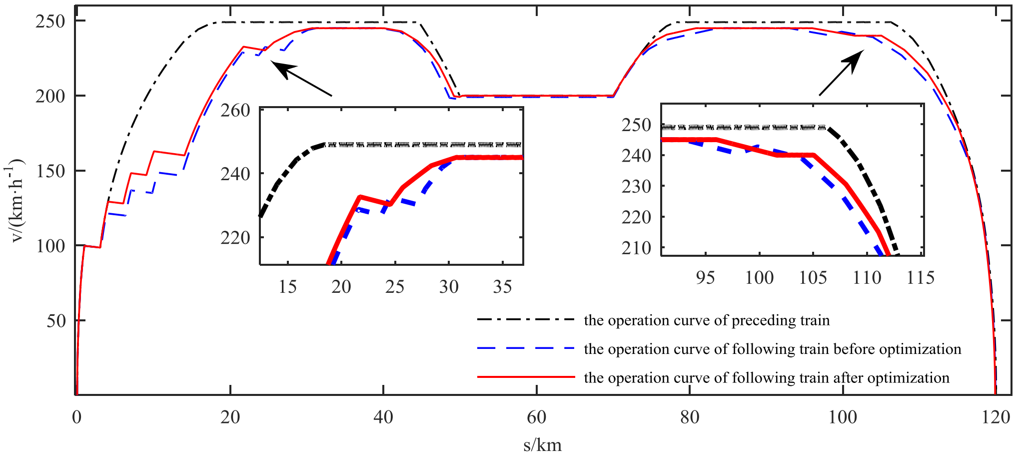

Fig.5 *v-s* curve

control principle of train following operation, until both of them operate with reasonable velocity and interval, to ensure a safe and efficient steady train-following operation state. According to the previous analysis, we know that the LMA calculated by minimum safety distance algorithm is higher than that calculated by the traditional algorithm. Therefore, the following train which adopts the optimal algorithm will be affected by the preceding train later than the one using the traditional algorithm.

The stretch-time curve of train following operation is shown in Figure 6. According the analysis mentioned above, it can be seen that the train safety interval is smaller than that derived from the traditional algorithm when the train running with the minimum safety distance mode. Therefore, when the train is operated according to the optimization algorithm, both the departure interval and arrival interval are smaller than that using the original algorithm.

It can be seen from Figure 6 that the running time of the preceding train is 2110 s, while that for the following train is 2177 s and 2208 s when controlled by the minimum safety distance optimization algorithm and the traditional algorithm, respectively. Therefore, the following train which adopts the optimization algorithm can reach the target destination earlier than the one using the traditional algorithm. The interval-time curves of preceding and following train are shown in Figure 7. From Figure 6 and Figure 7, it can be seen that the interval between two trains calculated by the optimization algorithm is shorter than that calculated by the traditional algorithm. It means the optimization algorithm can shorten the interval between the proceeding and the following train.

The velocity-time curve of the train following operation is shown in Figure 8. As can be seen in Figure 7 and Figure 8, after optimization, the following train can adjust its own behavior according to its current speed and the current safety following distance to make the actual following distance between two trains adjusted dynamically and rationally. As a result, based on the dynamic adjustment of the safe following distance of two trains, a safe and efficient train following operation can be achieved by such control method.

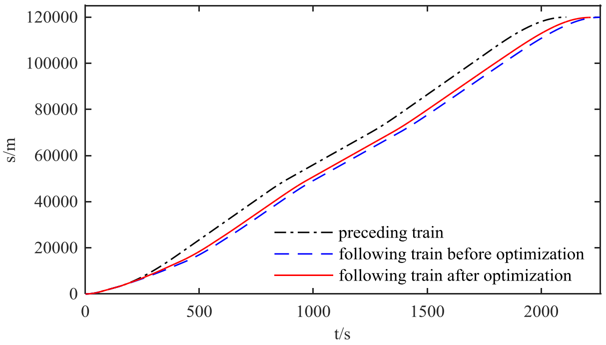

Fig.6 *s-t* curve

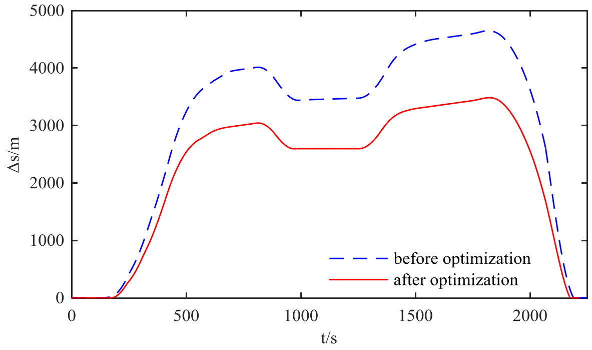

Fig.7 Δ*s-t* curve

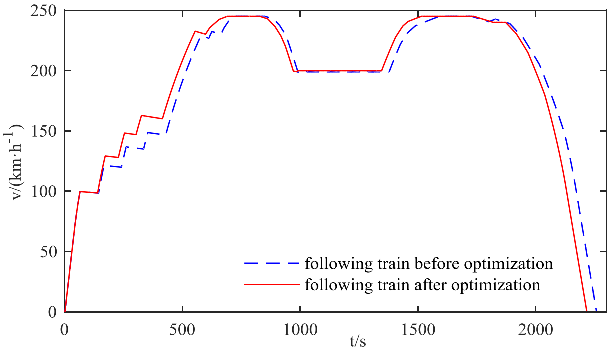

Fig.8 *v-t* curve

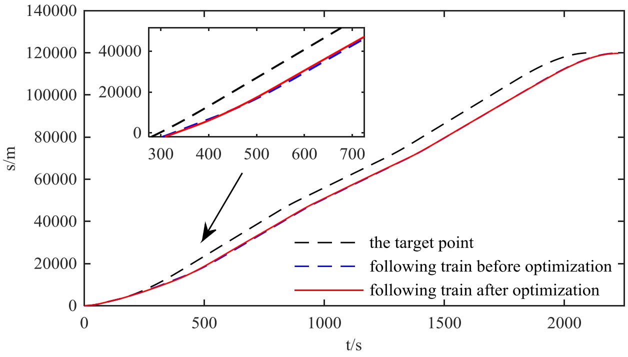

Fig.9 target point stretch curve

The time-varying curve of the stretch between the train and the target point is shown in Figure 9. It can be seen that when the train is operated under a train-following mode, the target point moves along with the movement of the preceding train. The following train operated with the designed calculation method that based on train-following operation adjustment control principle of the minimum safety distance model can keep up with the variation of the target point.

V. CONCLUSION

The dynamic control of the following distance of the high-speed train can be realized by scientific adjustment of the train's behavior. Under the premise of understanding the running state of the preceding train and the performance of train-following, a dynamic and reasonable control of the following distance of the train can be realized through the adjustment of its behavior. In the moving block system that based on the CBTC train control technology, information exchange including the performance parameters, operation state and control strategy between trains can be realized. Research on the train-following control under vary strategies can not only improve the efficiency and the safety, but also enhances the comfort of train during its behavior adjustment.

In this paper, the proposed model is realized as an improved form of the traditional safety distance model, which added the velocity information of the preceding train and also considered the braking of the train under the most unfavorable condition. The real-time calculation model of the minimum safety distance during following operation of the high-speed train is established. Based on this model, the control principle of the following control of the high-speed train with a safe and efficient condition is designed and is taken as a problem in terms of safe headway distance.

The simulation results show that the proposed algorithm can shorten the minimum safety distance effectively. The following train can operate more efficient and smooth under the premise of safety. The proposed algorithm is helpful for further research on the following control of the high-speed train under moving block.

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