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Research Article

A New Calibration Method for the Real-Time Calculation of Dynamic Safety Following Distance under Railway Moving Block System

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Only the actual following distance that is a little greater than the optimum safety following distance at any time can make the following train move in safety and efficiency. For this purpose, a new calibration method is studied for the real-time calculation of the dynamically optimum safety following distance. To cope with the complex situations of train following operation, the mathematic model of train deceleration operation based on the hyperbolic function with a variable acceleration control strategy is established to simulate the speed-changing behavior of high-speed train steered by the well-experienced driver. Using the evaluation of train behavior adjustment quality and the numerical analysis theory, we build the fitting function of the optimum absolute safety following distance changing with the following train's velocity for the real-time calibration of safe following distance under absolute braking mode. And then, we discussed the real-time calculation of the optimum safety following distance under relative braking mode (i.e., the relative safety following distance). The study results will help a high-speed train to evaluate and optimize its own following behavior according to the current operation states of train following system, the actual following distance, and the absolute or relative safety following distance. The actual following distance is rationally controlled by the scientific adjustment of the following train's behavior so that train following movement can be always safe, efficient, and smooth (comfortable).

1. Introduction

In fixed block system, the positioning and navigation service of train movement are provided by the track circuit and ground signaling. However, in moving block system it is replaced by the accurate positioning and navigation technology; the following distance shows the characteristic of "moving" and "length-changing" in the process of train following operation. For safety reasons, the following distance cannot be too short; for making full use of line transport capacity, the following distance cannot be too long. Therefore, there must be "an optimum safety following distance" at any time between two successive high-speed trains with following relationship. Due to the common view that safe following distance is often defined as the minimum following distance for collision avoidance, safe following distance is commonly referred to as "the optimum safe following distance".

During high-speed train following operation, the safe and efficient train following operation should be realized by the control of the actual following distance through the behavioral adjustment of the following train. The real-time calibration of dynamically safe following distance is undoubtedly one of the important technology bases for high-speed train to adjust its own behavior safely and efficiently.

The calibration of safe following distance must abide by the principle of "safety first" and take into account the full use of the line transport capacity under safe driving. That is to say, the actual following distance at any moment should not be too short or too long. Besides safety and efficiency, the smoothness (comfort) of train behavior adjustment is another factor to be considered in the calibration of safe

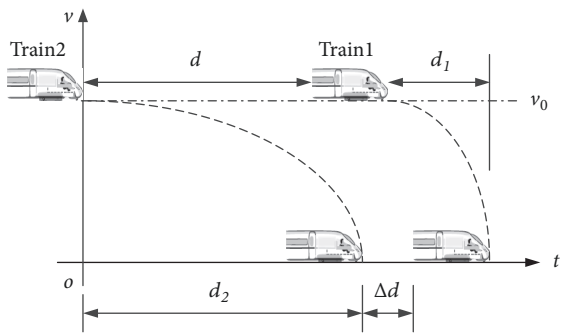


Figure 1: Traditional calculation of safe following distance.

following distance. Lamonde [1] proposed the criteria called "activity oriented ergonomics" for coordination at a distance design. In [2, 3], Tang et al. and Yang et al. used the empirical data to calibrate the speed-headway function and proposed a car-following model to investigate the effects of real-time road condition on each vehicle's speed, acceleration, headway, fuel consumption, CO, HC, and NO_X under uniform flow. The numerical results showed that under the smooth driving behavior the electric vehicle's battery life can be prolonged. Inspired from it, we will consider not only the safety and efficiency but also the smoothness (comfort) of train following movement for the calibration of safe following distance.

"IEEE Guide for the Calculation of Braking Distances for Rail Transit Vehicles [4]", promulgated by the Rail Transit Vehicular Interface Committee of the IEEE Vehicular Technology Society in 2009, can be used to calibrate the safe following distance under a certain following situation. However, the calibrated safety following distance is only a limited data set, from which we cannot get a safe following distance under any following situation. Generally, the safe following distance kept by the following train from the preceding train always changes with dynamic train following situation so that the safe following distance needs to be in real time calibrated at any time within the full-velocity field from 0 km/h to 500 km/h. At present, the velocity of high-speed train does not exceed 500 km/h.

In this paper, we will discuss and present a new method based on the hyperbolic function with a variable acceleration control strategy to realize the real-time calibration of safe following distance during train following operation.

2. Traditional Calculation Method of Safe Following Distance and Its Disadvantages

Figure 1 shows the traditional calculation method of safe following distance in railway transportation industry. Train1 is the preceding train and Train2 is the following train. They move with a constant velocity v_0. When Train1 slows down and stops, Train2 must brake to stop for collision avoidance. Suppose that the moment of Train1 starting to decelerate is the initial time, so d_1 is the distance traveled by Train1, d_2 is the distance traveled by Train2, Δd is the necessary safety margin, and d is the safe following distance which should be kept by the following train from the preceding train. As pointed out by Huang and Ren [7, 8], a vehicle (train) following controller is required to maintain a desired spacing between vehicles and to achieve good performance, which involves the safety of train operation and the density of the trains moving on a line.

The safe following distance under the following velocity v_0 can be expressed by the following equation:

$$d = d_2 + \Delta d - d_1 \tag{1}$$

If $d_1 = 0$, d is called the absolute safety following distance, which is the safe following distance under the absolute braking mode; if $d_1 \neq 0$, d is called the relative safety following distance, which is the safe following distance under the relative braking mode. The relative safety following distance can be calculated based on the absolute safety following distance by further considering the preceding train's running state and control strategy. It should be noted that (1) can be also used to calculate the safe following distance when the preceding and following trains move at different velocity. In consideration of the feasibility and complexity of engineering implementation, (1) was applied in train organization and control under the assumption of the preceding and following trains moving at the same velocity.

Since the late 1950s, Figure 1 and (1) have been used to compute the safe following distance under a certain uniform following velocity in road and railway traffic. Early in the last century, a lot of research had been done in order that the platoon/vehicle following control can maintain a constant spacing and avoid collision [8]. Tang et al. [9] introduced the two safety distances (i.e., the front safety distance and back safety distance) into the car-following model to explore their impact on vehicle's driving behavior. Solyom and Coelingh [10] analyzed the effects of fundamental limitations on the longitudinal and lateral control performance of a platoon and the effects on following distance, perceived safety, and fuel economy. The trade-off between minimizing fuel consumption and maintaining a safe following distance was analyzed and described. However, in the general case, the preceding and following trains keeping the same speed and the fixed optimum distance is an ideal state just during a very short time slice of the entire following process. It is inevitable for the preceding and following trains to adjust their own running states according to the current complex transport environment or demand in the following process. Obviously, the traditional calculation method of the safe following distance cannot reflect and be well applied to the complex process of train following operation. When the following train travels at a velocity different from that of the preceding vehicle, how to calculate the safe following distance between trains in real time? There must be an effect method to in real time calculate the safe following distance at any time during train following operation. (The velocity v_1 of Train1 and the velocity v_2 of Train2 may be equal or not equal to each other, as shown in Figure 2.) It is closely connected with not only the safety of high-speed train following operation but also the full utilization level of line transport capacity and the smoothness (comfort) of train behavior adjustment. It is one of the key and core data for the following train to evaluate its

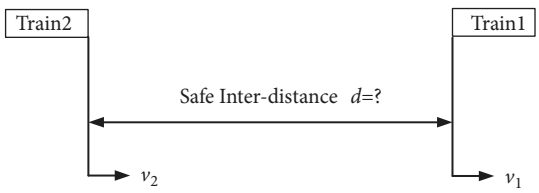


Figure 2: Dynamic situation of high-speed train following operation ($v_1 \neq v_2$).

own following quality at any time and adjust its own behavior scientifically.

Another outstanding problem of traditional calculation method of safe following distance is that some constant accelerations [11–13] are used to describe the control strategy of the following train's behavioral adjustment, but they do not conform to the actual feature of the train's acceleration changing gradually and the initial and terminal accelerations at the beginning and end of train behavior adjustment process are not equal to zero. Because different control strategies can be adopted by the preceding and following trains, the stopping distance d_1 or d_2 can have an unlimited number of values even if their velocities are equal. As a result, every value of safe following distance has many mapping relations with the velocities and control strategies of the preceding and following trains. Because the domains of definition and values of the safe following distance function are infinite multiple-valued space, if without a mapping regularity, it would be hard to determine a feasible industry standard of "safe following distance" for train organization and control. Especially in a large-scale railway transport network, without the industry standard of dynamic safety following distance it would be hard to realize the safe, order, and efficient train operation and organization under moving block system.

The mapping relations among the safe following distance, the velocities, and the control strategies of the preceding and following trains have to be regularized so that the description of the mapping relations has its feasibility and instructional meaning in engineering. The traditional calculation method has the significant disadvantages in the real-time calibration of the safe following distance mainly because it can only have the safe following distance to be calibrated under a limited number of typical following velocities and the preceding and following trains moving at the same velocity. Generally speaking, high-speed train always changes its own velocity to adapt itself to the new route conditions or the new following situation. The velocities of the preceding and following trains are difficult to be exactly same with each other in most of the time. The real-time calibration of the dynamic safety following distance within the full-velocity field can have a greater engineering value for the safe and efficient behavioral adjustment of high-speed train.

3. Calculation of Dynamic Safety Following Distance Based on the Hyperbolic Function

Dynamic safety following distance is the optimum following distance which should be kept by the following train away from the preceding train, but it always changes with train following situation. The so-called "optimum following distance" can be used by the following train to adjust its own behavior scientifically so that the safety, efficiency, and smoothness (comfort) requirements of train following operation can be satisfied by the behavioral adjustment of the following train, even in the worst situation such as natural disaster and broken rail causing the preceding train to stop abruptly. However, "safe following distance" cannot be simply understood as the safety requirement of train following operation. The efficiency of train following operation and the smoothness (comfort) of the following train's behavioral adjustment should also be taken into consideration to avoid the discomfort of the passengers and the damage to goods, improve the efficiency of train organization, and practice the transport concept of "service orientation".

3.1. Deceleration Model of High-Speed Train. According to [14, 15], the mathematical model of high-speed train decelerating to stop can be expressed as the following equation:

$$v = -(b+\delta) * \tanh(k * (t-\tau)) - b + v_0 \tag{2}$$

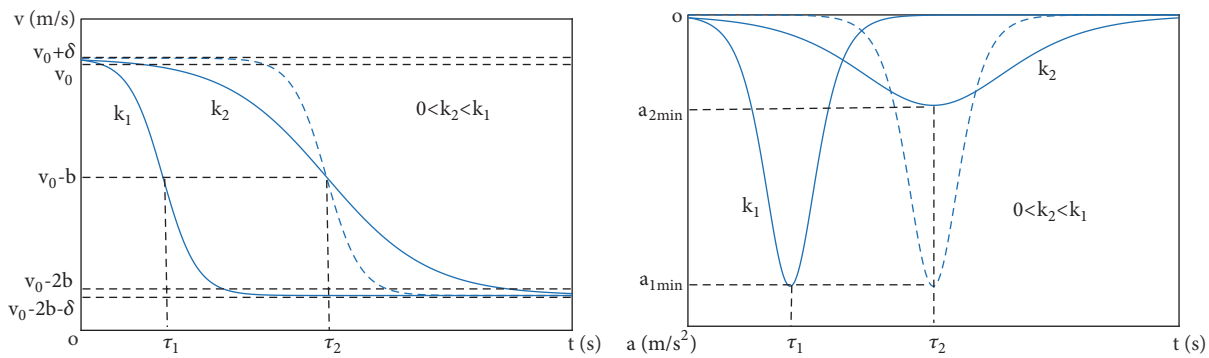
where v_0, b, k, and τ are the constants greater than 0, δ is a small positive constant, v is the velocity variable, t is time variable, and tanh() is the hyperbolic tangent function.

When $k = k_1, k_2$ ($0 < k_2 < k_1$), the v–t and a–t curves can be achieved as showed in Figure 3, where the curve indicated by the dotted line can be gotten by the horizontal movement of the $k = k_1$ curve along the x-axis.

Figure 3(a) describes the movement law of train decelerating from the initial velocity $v_0 + \delta$ to final velocity $v_0 - 2b - \delta$ under the condition of different k values. The two curves can be expressed by the monotonically symmetrical functions centered on the point $(\tau, v_0 - b)$, where $\tau = \tau_1$ or $\tau = \tau_2$. When $t \longrightarrow -\infty$, $v \longrightarrow v_0 + \delta$ and the acceleration tends to 0; when $t \longrightarrow +\infty$, $v \longrightarrow v_0 - 2b - \delta$ and the acceleration approaches 0. In the whole process of high-speed train's behavioral adjustment, there are at least one extreme point in any acceleration-time curve. Clearly, the acceleration-time curve with only one extreme point is easy to be realized by the control of train movement. Please see Figure 3(b).

The parameter δ is introduced into (2) because the engineering realization of train decelerating process should be taken into consideration. Clearly, when δ is determined, the traveled time and distance would vary with the value of k in the process of the train decelerating from the initial velocity v_0 to the final velocity $v_0 - 2b$. If $v_0 = 2b$, the train would decelerate from the initial velocity v_0 to 0 m/s. There is close correlation between the value of k and the steepness of the velocity-time curve. The value of k reflects not only the efficiency and smoothness (comfort) of train operation but also the control strategy adopted by a train in the restraint of its own performance, so (2) can accurately describe the behavioral details of a train steered by the well-experienced driver to decelerate and the general expectations people hold for the process of train decelerating.

3.2. Smoothness (Comfort) Evaluation of High-Speed Train Decelerating. The smoothness (comfort) evaluation index in



(a) Velocity-time curves (b) Acceleration-time curves

Figure 3: Decelerating behavior curves of high-speed train based on deceleration model.

the process of vehicle operation mainly involves "the absolute value of acceleration" and the "jerk" (the absolute value of the rate of acceleration change) [16, 17]. In [18], Castellanos and Fruett constructed an embedded system in which the acceleration and jerk magnitudes were used to evaluate the passenger comfort in public transportation.

By taking the derivative of (2) with respect to time, the acceleration function of train decelerating operation can be gotten as follows:

$$a = \frac{dv}{dt} = -k * (b + \delta) * \left(1 - \tanh^2 (k * (t - \tau))\right) \quad (3)$$

Since $\tanh^2(k * (t - \tau)) \leq 1$, the following equation can be gained.

$$\max (|a|) = k * (b + \delta) \quad (4)$$

which means that the absolute value of acceleration a is the maximum value when $t = \tau$.

By (3), we can get the time derivative of acceleration a:

$$\frac{da}{dt} = 2 * (b + \delta) * k^2 * \tanh^2 (k * (t - \tau)) * \left(1 - \tanh^2 (k * (t - \tau))\right) \quad (5)$$

and then the quadratic derivative of acceleration with respect to time can be gotten as follows:

$$\frac{d^2a}{dt^2} = 2 * (b + \delta) * k^3 * \left(1 - \tanh^2 (k * (t - \tau))\right) * \left(1 - 3 * \tanh^2 (k * (t - \tau))\right) \quad (6)$$

Clearly, the extreme point of da/dt accords with $\tanh^2(k * (t - \tau)) = 1$ and $\tanh^2(k * (t - \tau)) = 1/3$. In other words, there exist the maximum absolute values of da/dt during the period of train speed-changing operation. Here the analysis is given as follows.

(1) When $\tanh^2(k * (t - \tau)) = 1$,

$$\frac{da}{dt} = 0. \quad (7)$$

(2) When $\tanh^2(k * (t - \tau)) = 1/3$,

$$\frac{da}{dt} = \frac{4}{9} * (b + \delta) * k^2. \quad (8)$$

(3) Investigate the values of da/dt at the starting and terminal points of train speed-changing operation. When $t = 0$, $da/dt \longrightarrow 0$; when $t = 2\tau$, $da/dt \longrightarrow 0$. It means that the speed-changing process of a train has at least one extreme point from a steady state with uniform velocity to another one.

By (5) and (8) simultaneously, the maximum absolute value of the time derivative of acceleration can be taken as follows:

$$\max\left(\left|\frac{da}{dt}\right|\right) = \frac{4}{9} * \frac{(\max (|a|))^2}{b + \delta} \quad (9)$$

In general, the speed-changing interval $[0, v_0]$ of high-speed train decelerating to stop has a larger range but the absolute value of acceleration a is relatively small, as long as $\max(|a|)$ is chosen reasonably, $\max(|da/dt|)$ can generally satisfy the corresponding "jerk" index with the result that the smoothness and comfort of high-speed train decelerating operation can be ensured, i.e., $jerk = \max(|da/dt|) \leq 2.0\text{m/s}^3$ [16, 17]. Thus, the acceleration of train delivering to human body can be hardly felt and the damage caused by the abrupt change of train speed to the goods can be avoided.

3.3. Calculation of Dynamic Safety Following Distance. Theoretically, the mathematical model for the calculation of the dynamic safety following distance is shown in

$$d = \int_0^{T_2} v_2 * dt + \Delta d - \int_0^{T_1} v_1 * dt \quad (10)$$

where v_1 and v_2 denote the velocities of the preceding and following trains, respectively. T_1 and T_2 can be calculated by use of the initial velocities v_{10} and v_{20}, the final velocities 0 m/s of the preceding and following trains, and the velocity-time function of v_1 and v_2. Here, T_2 involves the lag time of the following train responding to the behavior change of the preceding train.

By the refusion and decomposition of (10), the real-time calibration of the absolute and relative safety following distances can be, respectively, realized. Please see Sections 4 and 5.

4. Real-Time Calibration of the Dynamic Safety Following Distance

The determination of the safe following distance is closely related to the braking mode adopted by high-speed trains. For the calculation of the safe following distance under the relative braking mode, i.e., the calculation of the relative safety following distance, the current running state of the preceding train, and its strategy of decelerating to stop under the worst condition should be taken into consideration.

4.1. Real-Time Calibration of the Absolute Safety Following Distance. If the following train can only get the current position of the preceding train or is going to stop at a fixed point, the absolute braking mode should be adopted for safety and accuracy. The mathematical model of calculating the absolute safety following distance is shown as follows:

$$d_{Absolute} = \int_0^{T_2} v_2 * dt + \Delta d \tag{11}$$

According to (11), the absolute safety following distance kept by the following train with any velocity from the preceding train can be calculated but the complex calculations would have an adverse impact on the real-time control. In practice, the calibrated safety following distance is just a limited data set. By (11), the standard values of absolute safety following distance under typical velocities can be determined because it is impossible in engineering to give an unlimited number of standard values for safety following distance under different following situation. However, the velocity of high-speed train is always changing continuously during its own behavioral adjustment due to its own inertia. The real-time calibration of the safe following distance within the full-velocity field from 0 km/h to 500 km/h should be solved at any time during the dynamic change of train following state.

The safety, efficiency, and smoothness (comfort) of train following movement need to be considered in the calculation of safe following distance, so there must be an optimum value of safe following distance under any following situation. We can establish the fitting function of the absolute safety following distance changing with the velocity of the following train, as shown below

$$d_{Absolute} = f\left(v_2(0)\right) \tag{12}$$

where $v_2(0)$ is the current (initial) velocity of the following train.

The position of each driver beginning to react toward the signal light is usually predefined as 220 m [19]; as for how to calculate the exact value of this position, Tang et al. [19] pointed out that some empirical or experimental data should be utilized to calibrate it in the future. Clearly, for the automatic control of unmanned vehicles, the position presented in [19] can be regarded as the stopping distance from a designated parking point to be calculated by (12).

Under railway moving block system, (12) can be used by the following train to in real time calibrate the absolute safety following distance from the preceding train according to its own operation state within the full-velocity field. If the absolute braking mode is adopted by a high-speed train when it decelerates to stop, the absolute safety following distance calculated by (12) would be one of the important basic data for its behavioral adjustment.

4.2. Real-Time Calculation of the Relative Safety Following Distance. The relative braking mode shall be adopted by train following system if the performance parameters, the current position, the running state information, and the control strategy of the preceding train can be in real time gotten by the following train.

If a high-speed train in its decelerating to stop adopts the relative braking mode, the following equation can be deduced by (10), (11), and (12) to calculate the relative safety following distance:

$$d_{Relative} = d_{Absolute} - d_1 \tag{13}$$

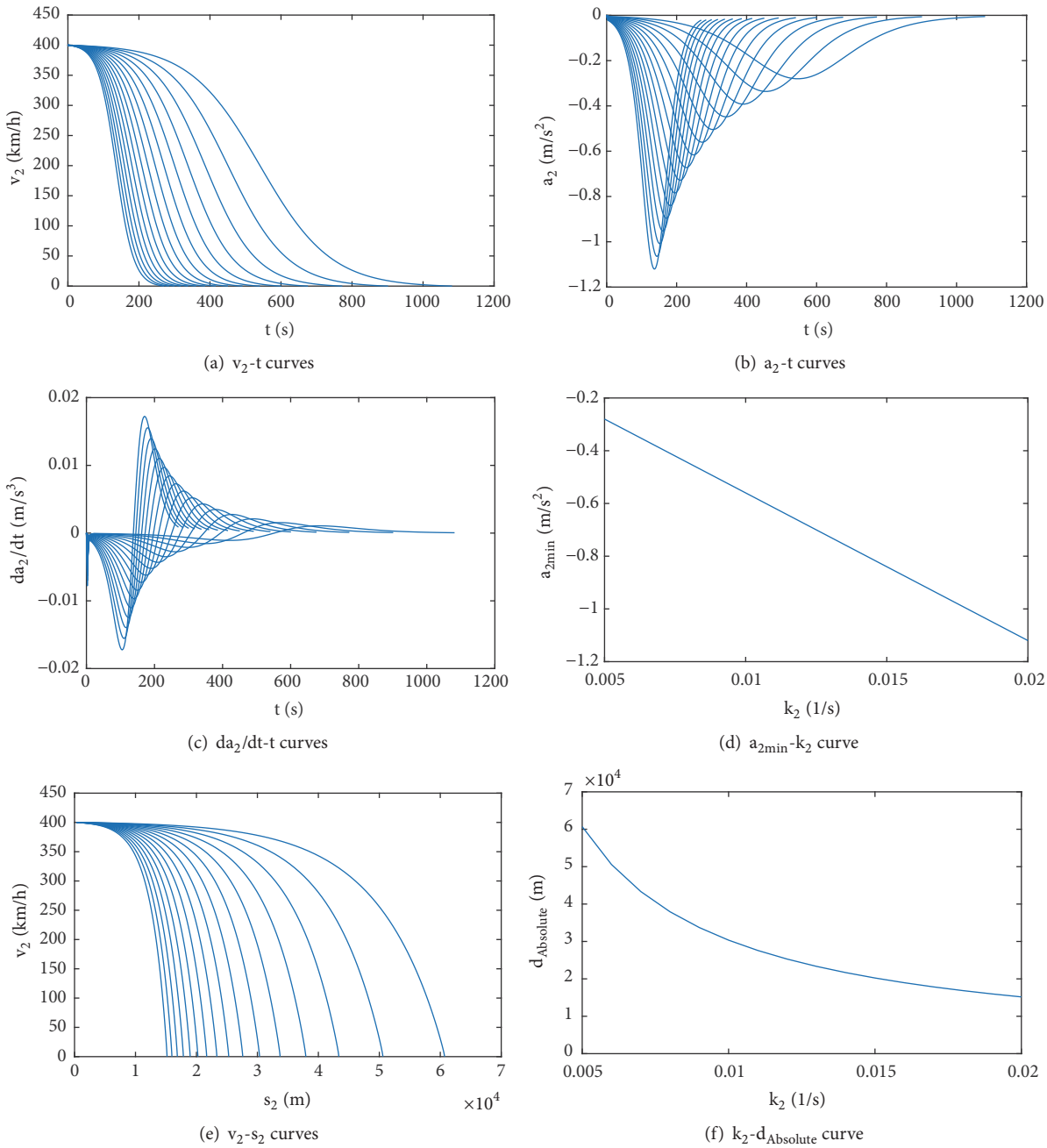
Then the real-time calibration of the relative safety following distance can be realized so that it can be taken as one of the basic data for the following train to adjust its own behavior.

The key problem lies in how to calculate the braking distance d_1 of the preceding train. The following train should in real time acquire the velocity of the preceding train and its current control strategy of decelerating to stop so as to solve the relative safety following distance $d_{Relative}$ according to (13).

Theoretically, as long as the velocity of the following train does not exceed that of the preceding train all the time, the rear-end collision would not happen forever. However, the time-delay exists in the adjustment behavior of the following train while it responds to the behavioral change of the preceding train. Because the preceding train may adopt a necessary decelerating strategy to stop at any time according to route condition, train command, emergency, etc., it is hard to ensure that the velocity of the following train is permanently lower than that of the preceding train. If no rule is made for the following distance control in the process of the preceding and following trains speeding up or the rule is too complex to perform, it is obviously disadvantageous to the safe and efficient following operation of high-speed train. In consideration of the preceding train abruptly decelerating to stop, according to the principle of "safety first", the emergency braking strategy of the preceding train under the worst condition would be used to calculate the relative safety following distance $d_{Relative}$ [20]. So the calculation of d_1 is shown in

$$d_1 = \int_0^{T_{1\_emergency}} v_{1\_emergency} * dt \tag{14}$$

where $T_{1\_emergency}$ is the period of the preceding decelerating from the initial velocity $v_{1\_emergency}(0)$ to $0\,\mathrm{m/s^2}$ and $v_{1\_emergency}$ is the "velocity-time" function of the preceding



(a) v_2-t curves (b) a_2-t curves (c) da_2/dt-t curves (d) a_{2min}-k_2 curve (e) v_2-s_2 curves (f) k_2-$d_{Absolute}$ curve

Figure 4: The behavioral details of the following train decelerating to stop.

train when it adopts emergency braking and can be gotten by (2).

In a similar way, we can get the fitting function of d_1 corresponding to its own various initial velocities when the preceding train stops abruptly, as shown below.

$$d_1 = g\left(v_{1\_emergency}(0)\right) \tag{15}$$

5. Simulation and Analysis

5.1. Real-Time Calibration of the Dynamic Absolute Safety Following Distance. Suppose the following train traces the preceding train at the velocity 400 km/h and $\delta = 0.5m/s$. Figure 4 describes the simulation results of the following high-speed train steered by the well-experienced driver decelerating to stop under different decelerating strategies ($k_2 = [5:1:20] * 10^{-3}$).

In the process of the following train decelerating to stop, the $v_2 - t$ curve gradually becomes gentle in the steepness along with the decrease of k_2, which denotes the control strategy of the following high-speed train (see Figure 4(a)). This judgment can be verified by the absolute value of the acceleration and jerk (jerk is defined as the absolute values of the change rate of acceleration) and the minimum

Table 1: Bipolar comfort evaluation standard for vehicle following control [5, 6].

Absolute value of acceleration $\lvert a\rvert$ (m/s^2)	Bipolar evaluation standard
≤0.315	very comfortable
≤0.63	comfortable
≤1	neither comfortable nor uncomfortable
≤1.25	uncomfortable
>1.25	very uncomfortable

acceleration (see the a_2-t curves in Figure 4(b), the da_2/dt-t curves in Figure 4(c), and the $a_{2\min}-k_2$ curves in Figure 4(d)). That is to say, the smoothness (comfort) of the following high-speed train decelerating to stop gradually increases along with the decrease of k_2. Figures 4(e) and 4(f) show the dynamic change of the following train's velocity and traveling distance in the process of its decelerating to stop under different decelerating strategies. Meanwhile, the smaller the value of k_2 is, the longer the absolute safety following distance the following train should keep away from the preceding train is. Conversely, the safe following distance would become shorter and the smoothness (comfort) of the following train stopping for safety would decrease along with the increase of k_2.

For the smoothness (comfort) of vehicle operation, the international standard organization provides the acceleration evaluation index in ISO2631 [5, 6] for reference, as shown in Table 1. On the other hand, Martinez and Canudas-de-Wit [16] pointed out that the design of train or elevator needs to satisfy the comfort requirement of the jerk less than 2 m/s^3.

Figures 4(a)–4(f) simulate the behavioral details of the following train steered by the well-experienced driver decelerating to stop with different control strategies, and Figures 4(b)–4(d) can be used to evaluate the smoothness (comfort) of the behavioral adjustment of the following train. Due to the fact that the jerk is always less than 2 m/s^3, the evaluation of smoothness (comfort) can only take the absolute value of acceleration into consideration. Clearly, the decelerating strategy k_2 of the following train with the initial velocity 400 km/h can be determined and satisfy the standard of smoothness (comfort). Thus the v_2-t curves of the following train decelerating to stop can be determined correspondingly, that is to say, the parameters of v-t function described by (2) can be determined for the following train. And then the optimum absolute safety following distance, kept by the following train away from the preceding train under the initial velocity 400 km/h, can be determined to be about $2.76 * 10^4$ m, as shown in Table 2.

Similarly, we can get the corresponding absolute safety following distance under other typical initial velocities such as 500 km/h, 450 km/h, 350 km/h, 300 km.h, 250 km/h, 200 km/h, 150 km/h, 100 km/h, 50 km/h, and 0 km/h (see Table 2). And then the parabola fitting function of the

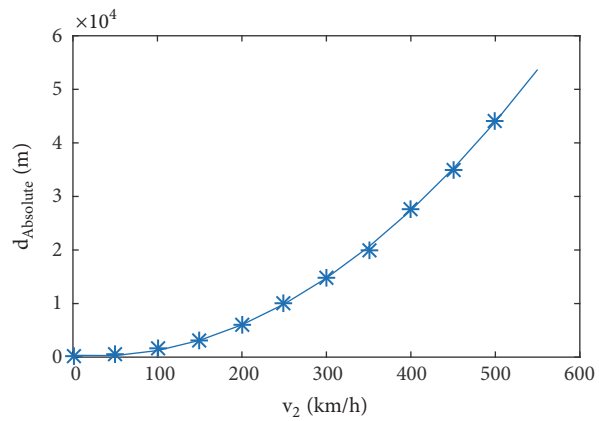


Figure 5: The fitting curve of the absolute safety following distance changing with the velocity of the following train.

(optimum) absolute safety following distance changing with its own velocity can be gotten as follows:

$$d_{Absolute} = 0.20 * v_2(0)^2 - 10.64 * v_2(0) + 331.33 \quad (16)$$

The fitting curve is shown in Figure 5.

5.2. Real-Time Calibration of the Dynamic Relative Safety Following Distance. When the preceding train brakes to stop in emergency, the fitting function $d_1 = g(v_{1\_emergency}(0))$ can be obtained in a similar way, as shown in (15), so the following train can use (13) and (16) to dynamically calculate the relative safety following distance $d_{Relative}$ away from the preceding train. It is clear that the calculation of $d_{Relative}$ can apply to the general following situation of the preceding and following trains moving at different velocity within the full-velocity field. The complex route condition such as ramp, and curve and the time delay of information transfer caused by the train-ground or train-train communications can be taken into further consideration based on the early results.

A point worth emphasizing is that the acceleration index of ISO2631 [5, 6] may be excessively rigorous for the evaluation of smoothness (comfort). According to the mathematical model adopted to simulate the tracking behavior of high-speed train steered by the well-experienced driver, as shown in (2), the acceleration shows the characteristic of "changing gradually" and the extreme value point exists in the acceleration-time curves no matter what value of k_2 is used as the stopping strategies of the following train (see Figure 4(b)). In this paper, $\max(\lvert a\rvert) \le 0.63 m/s^2$ is adopted as the constraint condition of determining the control strategy k_2 of the following train to ensure the behavioral smoothness (comfort) in the process of its decelerating to stop. It is different from the smoothness (comfort) index of $\lvert a\rvert \le 0.63 m/s^2$ provided by ISO2631. It seems that the smoothness (comfort) standard of acceleration could be properly relaxed in the permissible range of high-speed train performance to reduce the optimum absolute safety following distance under different velocity for the improvement of the efficiency of safe train following operation. But what extent should the index

Table 2: Optimum safety following distance under different velocities.

Velocity (km/h)	500	450	400	350	300	250	200	150	100	50	0
Optimal safety following distance $d_{Absolute} * 10^4$ (m)	4.41	3.51	2.76	2.01	1.47	0.99	0.61	0.32	0.15	0.047	0

of the smoothness (comfort) be relaxed to? It requires to be determined and verified in the field experiment of high-speed train behavioral adjustment.

5.3. Implementation of Dynamic Safety Following Distance within the Full-Velocity Field. Here below is the implementation step of the real-time calibration method of the safe following distance within the full-velocity field applying to high-speed train following control.

Step 1. The following train calculates the absolute safety following distance according to the fitting function (see (12)) under the absolute braking mode.

Step 2. The following train decides whether to adjust the safe following distance or not according to the braking mode adopted by itself.

Step 3. The following train determines the safe following distance kept from the preceding train according to the adopted braking mode in its following process and the corresponding control strategy of its following operation.

Step 4. The following train adjusts its own behavior according to the adopted optimum control strategy till the described safe following distance is achieved.

Figure 6 shows the implementation process of the real-time calibration of the safe following distance within the full-velocity field under the absolute or relative braking mode. The absolute or relative safety following distance is in real time calculated by (12) or (13) while the actual following distance can be measured in real time. The measurement of the actual following distance can learn from [21], in which Daponte et al. designed a speed and proximity measurement system based on traffic safety nodes of the wireless active guardrail system for road safety.

The real-time calibration method of the safe following distance within the full-velocity field contributes to the high-speed train adopting reasonable following control strategy in the complex transport environment and ensuring safety, efficiency, and the smoothness (comfort) of its own behavioral adjustment.

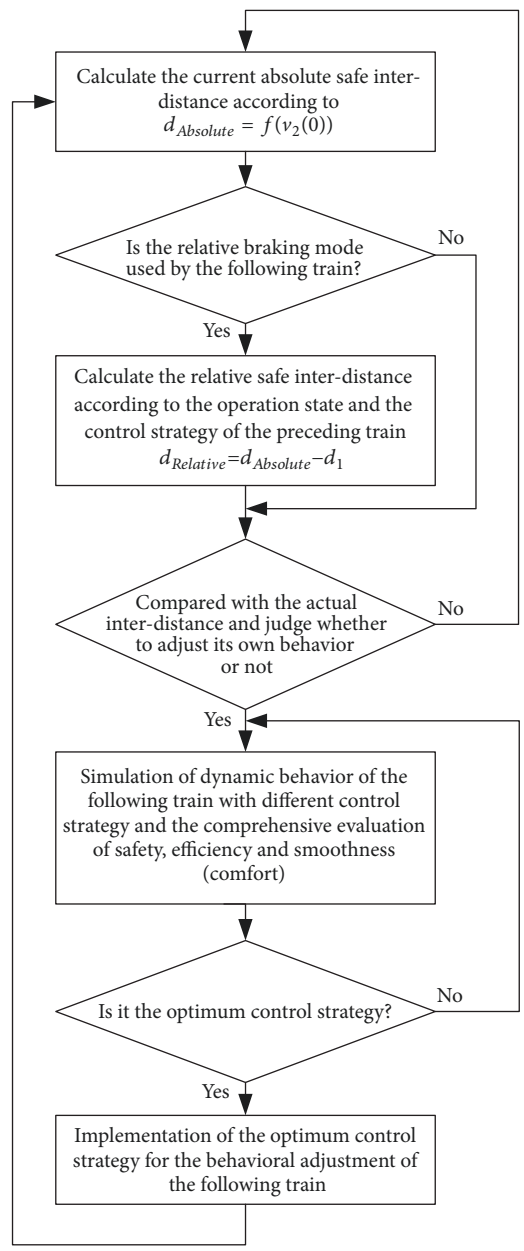
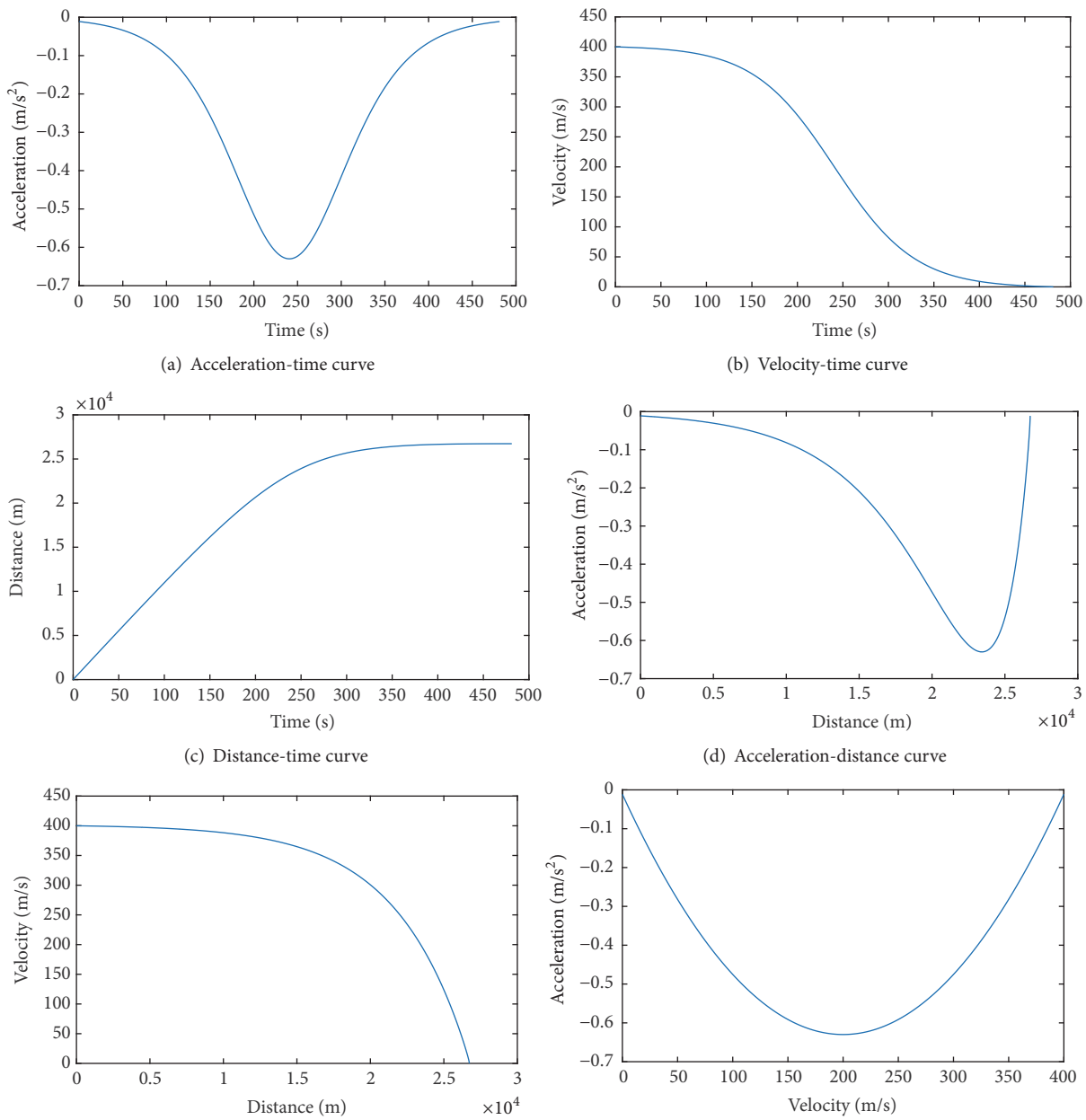


Figure 6: Implementation process of the real-time calibration of the safe following distance within the full-velocity field.

5.4. A Case of Simulation. Without loss of generality, we take a high-speed train stopping in front of a designated parking point for example here. Assume that the train moves at a constant speed of 400 km/h. According to (16), the train should begin to brake at a position that is $2.8075 * 10^4$ m away from the designated parking point. In the process of the train braking to stop at the designated point, the initial and terminal decelerations of the train are zero. Clearly, a symmetric deceleration-distance curve with the only extreme point, as shown in Figure 7(a), is the most concise and reasonable for the adjustment of train behavior under optimal control. That is to say, the deceleration of the train from 400 km/h to 0 km/h needs to experience two stages: from 0 to



(a) Acceleration-time curve

(b) Velocity-time curve

(c) Distance-time curve

(d) Acceleration-distance curve

(e) Velocity-distance curve

(f) Acceleration-velocity curve

Figure 7: The behavioral details of the train stopping in front of a designated position.

$a_{\min}$ and from $a_{\min}$ to 0. $a_{\min}$ is equal to -0.63 m/s^2 for comfort consideration.

For the train with the initial velocity of 400 km/h, at a position that is $2.8075 * 10^4$ m away from the designated parking point, by controlling its behavior according to the acceleration-time curve in Figure 7(a) that can be expressed into the form of (3), we can get the behavior details of the train in its whole stopping process, as shown in Figures 7(b)–7(f), the train takes 481.20 s and runs $2.6733 * 10^4$ m to stop completely. $\max(|da/dt|) = 0.0055\,\mathrm{m/s^3}$. Clearly, the safety and comfort (smoothness) can be met by the behavioral adjustment of the train under control.

6. Comparative Analysis of the Safe Following Distance Calculation between Railway and Highway Transportation

Many studies on the safe following distance calculation can be found in the field of highway transportation because both vehicle following control and vehicle cruise control must attach importance to the safety and efficiency of vehicle following operation. Based on Newton's kinematics formula and molecular dynamics, Qu et al. [22] discussed the modeling and calculation of car-following required safety distance, covering longitudinal and lateral safe distance; however,

the gradually changing of the follower's deceleration is not reflected in the process of its braking until it stops completely because the maximum deceleration of the follower was used to calculate the required safety distance. The importance of autonomous intelligent cruise control function, which can provide automatic control of both vehicle speed and distance in relation to the preceding vehicle, has been recognized by Richardson and Smith [23] in the early 1990s, According to the desired speed and the desired following distance given by this function, the throttle and brake actuators can be incorporated to control the distance and relative velocities between a vehicle and the vehicle in front. Bertolazzi, et al. [24] described a novel driver-support system that helps the following vehicle to maintain the correct speed and headway (distance) with respect to lane curvature and other vehicles ahead. The system intervenes only when a problem is actually detected in the headway and/or speed (approaching curves or objects) and has been shown to cause prompt reactions and significant speed correction before getting into really dangerous situations. However, how to calculate the dynamic safety distance in real time in the complex traffic environment? References [23, 24] did not give it a detailed description. Chien and Ioannou [25, 26] first proposed the calculation formula of the dynamic safety following distance as shown in

$$d_{safe} = \lambda_1 \left(v_f^2 - v_p^2\right) + \lambda_2 v_p + \lambda_3 \tag{17}$$

where v_p and v_f are the velocities of the preceding and following vehicle, respectively, at any time. λ_1, λ_2, and λ_3 are constants. Martinez and Canudas-de-Wit [16] pointed out the deficiency of (17): "This model assumes that the vehicles have identical and constant decelerations during the braking maneuver. The latter assumption produces solutions with high jerks and, consequently, low comfort. In addition, this model could produce the undesirable large following distances." A novel reference model-based control approach for automotive longitudinal control was proposed to provide dynamic solutions consistent with safety constraints and comfort specifications. Somda et al. [17, 27] presented an exponential model with a safe, robust, and comfortable strategy for vehicle longitudinal control. According to the academic view point of Martinez and Canudas-de-Wit [16], the safe following distance, acceleration, and jerk (time derivative of acceleration) were considered as three indexes to evaluate vehicle behavioral quality. Clearly, the safe interdistance cannot be always calculated correctly by (17) for vehicular behavior adjustment in safety, efficiency, and smoothness (comfort) during the fast-changing vehicle following situation. On the other hand, there are differences in the calculation formulas of the absolute and relative safety following distances because of the different considerations for the control strategies and velocities of the preceding and following vehicles. It can be seen that the control strategies of the preceding and following vehicles did not cause sufficient consideration in (17). Martinez and Canudas-de-Wit [16] defined green, orange, and red zones to characterize different safety levels for safe vehicle longitudinal control according to the difference between the actual and safe following distance. However, the real-time threshold values for judging these three zones in dynamic vehicle following environment need to be further studied. In consideration of the dynamic change of train following situation and the requirements of train movement control, the calculation of safe following distance must be able to meet the demands of real-time performance and the full-velocity field under any following situation. The proposed calculation method of safety following distance is established in forms of the fitting function, which integrates the hyperbolic function with numerical analysis. It can apply to not only railway moving block system but also highway transportation.

7. Conclusion

In the moving block system, the safe following distance changes dynamically with the following situation just as the actual following distance. The real-time calibration technique of the dynamic safety following distance within the full-velocity field is undoubtedly important to the control of high-speed train following operation. At present, the high-speed train mainly adopts the speed control mode of "distance-to-go" for its movement and behavioral adjustments. However, the speed control mode of "distance-to-go" does not involve the real-time calibration of the dynamic safety following distance so that by this control mode the quality of high-speed train following motion cannot be evaluated more comprehensively. In fact, not only the problem of high-speed train braking to stop should be firstly considered according to the principle "safety first", but how to improve the efficiency of train following operation should also be considered under the premise of safe driving. On the other hand, for safe following distance, besides the evaluation indexes of safety and high efficiency, the smoothness of high-speed train adjusting its own behavior should also be ensured to avoid the uncomfortableness of passengers or the damage to goods. This paper goes much deeply into the real-time calibration technique of dynamic safety following distance within the full-velocity field and puts forward the mathematical model which can simulate the whole process of the following train steered by the well-experienced driver braking to stop, and the numerical analysis is used to realize the real-time calibration of dynamic safety following distance within the full-velocity field. The moving block system has not been applied to the railway transportation but can be found in urban rail transit system with the velocity between 0 and 80 km/h, which is far below that of railway transportation, and of which the traction weight, network topology, transport environment, and train organization are far less complex than that of railway transportation. There are still many difficulties in transplanting train control technology of urban rail transit system into high-speed railway transportation system, so the research of "the real-time calibration technique of the dynamic safety following distance within the full-velocity field" is of greater strategic importance and needs to be further verified, improved, and perfected in the future railway moving block system.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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