Multi-vehicle Cooperative Reliability Assessment of Urban Rail Transit

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Abstract. As the main way to solve urban public transportation problems, urban rail transit was widely used with the characteristics of energy saving, high traffic density, full-time and less pollution. However, multi vehicle operation is easily affected by random factors such as climate and environmental change. The reliability and safety of multi vehicle operation is especially important. This paper establishes a reliability model of multi vehicle cooperation by analyzing the braking process of cooperative vehicle and investigates the safety conditions that need to be met. Based on the safe running distance of vehicle, the two-vehicle cooperative operation model and unified reliability model are built. To analyze the influence factors of reliability model, the communication delay, driving distance, relative speed and braking performance are studied under multi-vehicle cooperation. The results show that above four factors impact on the safe braking of the vehicle, especially to the communication delay. The proposed reliability model can accurately evaluate the reliability of the vehicle's cooperative braking process and ensure the safe operation.

Keywords: Multi-vehicle cooperation, reliability model, urban rail transit, communication delay, vehicle tracking operation

1. INTRODUCTION

Vehicle control system is a key technology to ensure the safe and efficient operation of urban rail transit [1], which provides a strong guarantee for the development of urban economy and eases traffic pressure [2]. At present, the Communication Based Train Control (CBTC) uses wireless communication to replace traditional track circuits to achieve two-way large-capacity data transmission between trains and ground [3], which effectively improves train operation safety and operational efficiency. It is the main method of the current subway train control system. CBTC systems are typically data-driven systems, whose functions are realized relying on a variety of types of data configured in the Data Storage Units (DSU), for describing geometric traffic information, track auxiliary equipment layout, train configurable properties, and so on, in particular applications [4]. A CBTC signaling system permits a closer operation of consecutive trains within the safety distance, reducing the commercial headway in metro lines.[5]

However, the urban rail transit system has the characteristics of complex system distribution, large operating environment changes, high traffic density and strong randomness of vehicle operating parameters [6], and its control system requires ultra-high reliability. Once the urban rail transit control system fails, it will not only cause delays to passengers [7], but also cause safety accident. As an important part o6f the urban rail transit control system, the reliability of the CBTC system directly affects the operating efficiency and vehicle safety. Therefore, the reliability analysis of the CBTC system will help improve the overall operating performance of urban rail transit.

The main issue of urban rail transit is poor braking ability because the track has low friction and the path is fixed, and obstacles cannot be avoided. Therefore, from the most basic point of view, the goal of the CBTC system is to prevent trains from colliding and derailing [8]. Train operation is a dynamic process. The automatic control mechanism of the CBTC system will adjust the train speed in real time based on the status information of the current train and the preceding train and the line restriction information to maintain the safe running distance between the front and rear cars. It is necessary to evaluate the reliability of the cooperative operation of trains based on the running status of the trains. As a typical complex distributed real-time system, the CBTC system relies on stable, real-time, reliable data communication for its normal operation [9]. Xu et al. established the Markov model of the Data Communication System (DCS) structure for the redundant and non-redundant structure of DCS in the CBTC system to analyze its reliability and availability [10]. Lin et al. introduced the communication technology to realize train collision protection based on the existing train control system, designed the overall architecture of the system, and analyzed the simplified system through the reliability block diagram [11]. Liang et al. established a communication system reliability model based on deterministic and stochastic Petri nets (DSPN). Based on the actual line communication performance parameters, pi-tool is used to simulate and solve the DSPN model, and the reliability index of the system is obtained [12]. However, at present, the research content of the reliability modeling and simulation of CBTC system cooperative operation is rare. In the modeling method, there are shortcomings such as the difficulty of matching the model, the difficulty of verification, and the inability to change with time.

In this paper, by analyzing the braking process of cooperative train operation and the safety conditions that need to be met, the reliability evaluation model of multi-train cooperative braking is established to realize the reliability evaluation of this process. The paper is organized as follows: Section II analyzes the safe distance for train operation. Reliability model of multi-train cooperative braking is established in Section III. In Section IV, a multi-vehicle collaborative braking simulation is carried out, and its reliability is analyzed and evaluated. Conclusions are drawn in Section V.

2. SAFE DISTANCE FOR TRAIN OPERATION

According to the principle of moving block [13], the minimum distance of the section tracking train is satisfied:

$$L_{\min} = L_C + X + l \tag{1}$$

where $L_{\min}$ is the minimum distance of the section tracking train; L_C is the distance traveled by the train during the braking delay; X is the braking distance; l is the length of the train.

The above formula is obtained under the condition that the exact position of the preceding train is known. However, to ensure safety, the train safety distance L in the actual CBTC is longer than $L_{\min}$, that is, a minimum safety distance L_S is added. Then the minimum instantaneous distance of the section tracking train is:

$$L = L_C + X + l + L_S \tag{2}$$

3. RELIABILITY MODELING OF MULTI-TRAIN COOPERATIVE BRAKING

The CBTC system makes full use of communication means to transmit real-time information between the ground and the train. The next train will obtain the information of the previous train in real time, calculate and drive with the best braking curve, so as to improve the capacity of the section [14]. The train is usually not running at a constant speed, it will adjust the running speed according to the specific situation. Therefore, under the train tracking strategy of the moving block, it can be divided into the following two kinds of cooperative braking reliability problems: the reliability of the two-train cooperative braking when the preceding train is at a stop and the reliability with the preceding train at a constant speed.

3.1. The reliability of the two-train cooperative braking with the preceding train stopped

When the front train is in a stopped state, after receiving the state of the preceding train, the following train should make corresponding braking actions to ensure that the braking can be completed beyond the minimum safe distance. The braking process is shown in Figure 1.

At this time, the following formula is satisfied to ensure safe braking of the train.

$$L > X + L_S + l \tag{3}$$

The reliability model of train cooperative braking can be described as：

$$R(t) = P(L(t) > X(t) + L_S + l) \tag{4}$$

It is assumed that the movement state of the following train is stable from the stop of the preceding train, that is, the speed V is a constant value. Currently, due to the communication delay, the following train does not immediately take braking measures, but continue to maintain the speed V for a certain distance. Assuming that the communication delay is Δt , the condition for safe braking is:

$$L - L_C > X + L_s + l \tag{5}$$

Where $L_C = V \cdot \Delta t$.

The reliability model of train cooperative braking is:

$$\begin{aligned} R(t) &= P(L(t) - V \cdot \Delta t > X(t) + L_S + l) \\ &= P(\Delta t < \frac{L(t) - X(t) - L_S - l}{V}) \end{aligned} \tag{6}$$

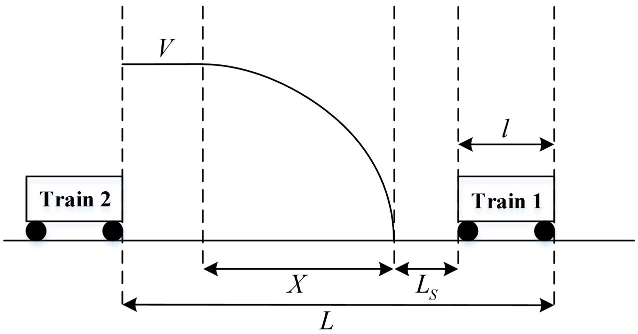

Fig. 1 Safe distance of train braking

3.2. The reliability with the preceding train at a constant speed

When the train in front decelerates and enters a stable state, the following train should also make corresponding braking actions after receiving the state of the train in front to ensure that it can decelerate beyond the minimum safe distance. The deceleration process is shown in Figure 2.

At this time, the following formula needs to be satisfied to ensure the safe braking of the train.

$$L_h(t) > X(t) + L_s + l \tag{7}$$

Then, the reliability model of train cooperative braking is:

$$R(t) = P(L_h(t) > X(t) + L_S + l) \tag{8}$$

It is assumed that when the speed of the preceding vehicle is stable, the motion state of the following vehicle is also stable, that is, the speed V_1 and V_2 are constant values. At this time, due to the communication delay, the following train does not immediately take braking measures, but continue to maintain the speed V_2 for a certain distance, and the preceding train will also run for a certain distance at the speed V_1. Assuming that the communication delay is Δt , the condition for safe braking is:

$$L_q(t) - V_2 \cdot \Delta t = L_h(t) - V_1 \cdot \Delta t \tag{9}$$

Incorporating Eq. (7) into the above formula, the condition for safe braking at this time can be obtained as:

$$L_q(t) - \Delta V \cdot \Delta t > X(t) + L_S + l \tag{10}$$

In this case, the reliability model of the following cooperative braking can be described as:

$$\begin{aligned} R(t) &= P(L_q - \Delta V \cdot \Delta t > X + L_S + l) \\ &= P(\Delta t < \frac{L_q(t) - X(t) - L_S - l}{\Delta V}) \end{aligned} \tag{11}$$

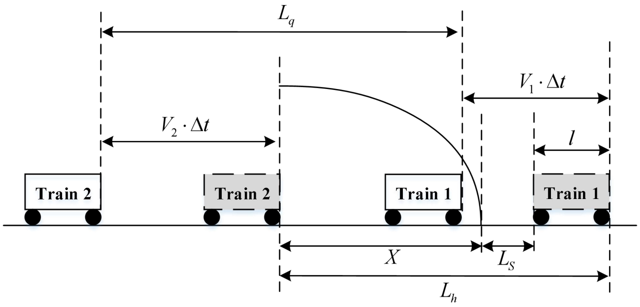

Fig. 2 Safe braking deceleration process

3.3. Reliability model of two-train cooperative braking

Through the analysis of the above two processes, the reliability analysis problem of train cooperative braking can be summarized into a model as followed:

$$\begin{aligned} R(t) &= P(L(t) - V \cdot \Delta t > X(t) + L_S + l) \\ &= P(\Delta t < \frac{L(t) - X(t) - L_S - l}{\Delta V}) \end{aligned} \tag{12}$$

where ΔV is the relative speed of the trains. Furthermore, the reliability model of train cooperative braking can be abstracted into a multi-parameter model:

$$R(t) = f(\Delta t, \Delta V, L(t)) \tag{13}$$

It can be seen from the model that the time delay, the relative speed of the trains and the distance between trains are the main factors to ensure the safe braking of the train.

3.4. Reliability Evaluation Model of Multi-train Cooperative Braking

The reliability model based on the two-train tracking process can be extended to the reliability analysis of multi-train tracking on the same line. The operation of trains on the same line is mainly affected by the operating state of the previous train. Therefore, the reliability evaluation model of multi-train cooperative braking can be obtained as:

$$R_{all}(t) = \prod_{i=1}^{n-1} R_i(t) \tag{14}$$

4. SIMULATION AND RELIABILITY EVALUATION OF MULTI-TRAIN COOPERATIVE BRAKING

Using the multi-train cooperative braking reliability model established in the previous section, a Matlab program was written to solve and evaluate the reliability of train operation. According to experience, set the initial values of the parameters are shown in Table 1.

4.1. The relationship between single parameter and reliability

In the process of multi-train braking, communication delay, distance between trains, relative speed and braking performance determine the safety and efficiency of train operation. Therefore, the relationship between these parameters and the reliability of multi-train cooperative braking is discussed in turn here.

Table 1 Simulation parameters of train cooperative braking

Symbol	Unit	Value
l	m	100
L_S	m	50
L	m	300
a	m/s^2	2
V_1	m/s	20
V_2	m/s	0

The relationship between the reliability of the train and the distance between trains in the process of cooperative braking is obtained. When considering that the communication delay is evenly distributed within a certain range, the distance between trains is gradually shortened from 300m, and the change process of train cooperative braking reliability is shown in Figure 3. The results show that the farther the distance between trains, the higher the reliability, and the change of reliability is a very fast process. When the distance between trains is shortened to 250.8 m, the reliability of train operation begins to drop sharply, and when it is shortened to 250.4 m, the reliability drops to zero. Therefore, the distance between trains should exceed 250.8 m in order to ensure the safe operation of trains. Once the driving distance is too small, safety accidents may occur.

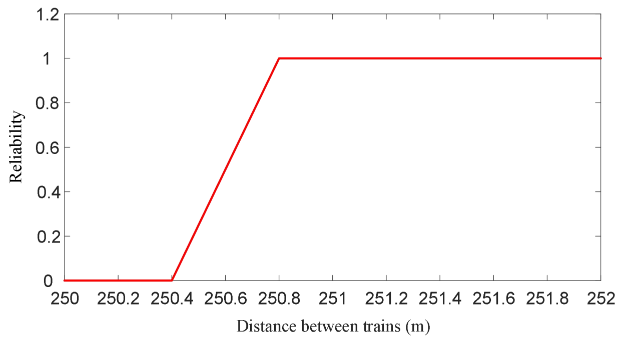

Fig.3 Relationship between driving distance and reliability

Analyze the impact of train braking performance on the reliability of train cooperative braking. When the communication delay is evenly distributed within a certain range, the braking performance of the train will gradually decrease, and the reliability change process is shown in Figure 4. The results show that the better the braking performance, the higher the reliability. Similarly, the reliability changes rapidly. When the braking acceleration is less than 1.341 m/s^2, the reliability of train operation drops to zero. Therefore, the poor braking performance of trains may cause safety accidents.

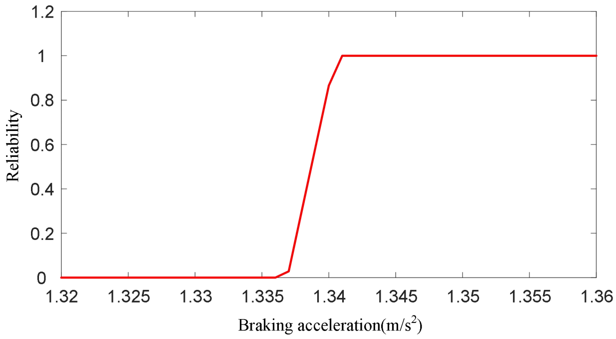

Fig.4 Relationship between braking performance and reliability

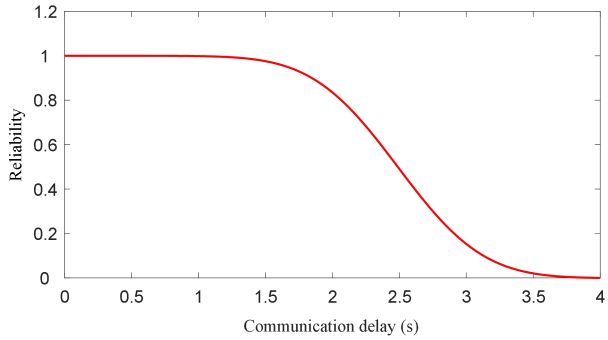

Fig.6 Relationship between communication delay and reliability

Further analyze the influence of train speed on reliability. Also consider that when the communication delay is evenly distributed within a certain range, the relative speed of train operation gradually increases, and the change process of reliability is shown in Figure 5. The results show that the slower the train, the higher the reliability. Similarly, reliability changes rapidly. When the relative speed exceeds 24.41 m/s, the reliability of train operation is very low. Therefore, if the train speed is too fast, it is easy to cause safety accidents. It should be ensured that the relative speed of the train is less than 24.41 m/s.

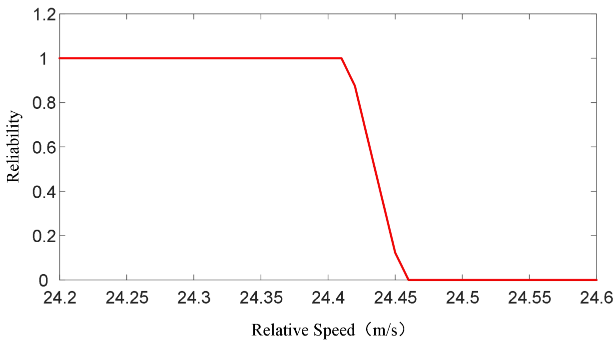

Fig.5 Relationship between relative velocity and reliability

From the above results, when the train communication delay is within the normal range, the running velocity and braking performance are guaranteed, and the train operation is safe and reliable.

Then analyze the influence of communication delay on the reliability of train operation. The CBTC system has strict requirements for communication delay [15]. Long-term communication delay or communication interruption may cause train derailment and collision [16]. Considering the fluctuation of the braking performance of the train, the braking distance is normally distributed, so that the communication delay time gradually increases from 0, and the process of obtaining the reliability change is shown in Figure 6.

It can be seen from the simulation results that as the communication continues to increase, its reliability continues to decrease. When the communication delay is greater than 2s, the reliability of train operation is lower than 0.8. Therefore, if the communication delay time exceeds a certain threshold, the safe operation of the train cannot be guaranteed.

4.2. The influence of communication delay and other parameters on the reliability

Driving distance, relative velocity, braking performance and communication delay will affect the reliability of train operation, and communication delay is the main parameter that affects the reliability of train operation. Therefore, the influence of communication delay and other parameters on the reliability of train operation is further considered. Through simulation, the reliability changes under the combined action of driving distance and communication delay, relative speed and communication delay, and braking performance and communication delay are obtained respectively, as shown in Figure 7, Figure 8 and Figure 9.

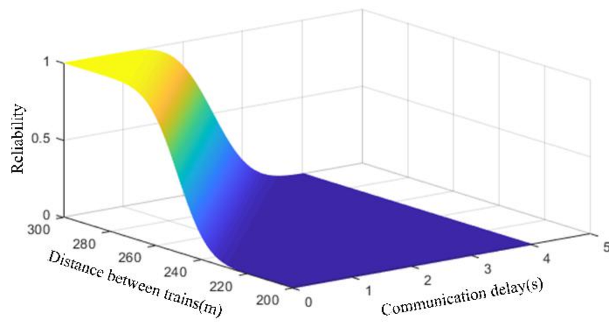

Fig.7 The impact of driving distance and communication delay on reliability

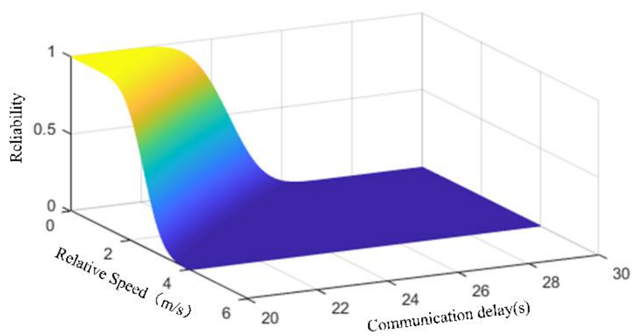

Fig.8 The impact of relative velocity and communication delay on reliability

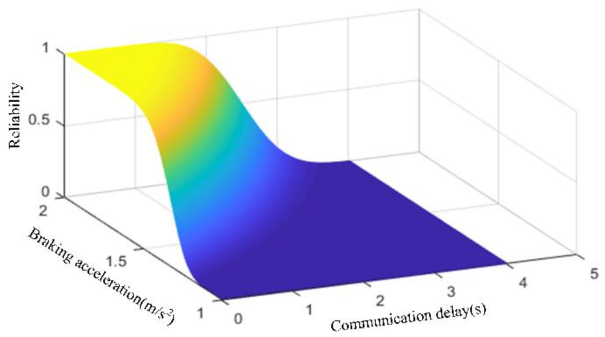

Fig.9 The impact of braking performance and communication delay on reliability

From the analysis of the above simulation results, it can be known that due to the joint action of multiple parameters, within a certain communication delay range, the driving distance, relative speed and braking performance will have different effects on the reliability of train operation. Therefore, in the process of train operation, it is particular important to ensure the safe operation of trains through the establishment of reliability evaluation models and the use of real-time operation to perform reliability analysis.

4.3. Reliability Evaluation of Train Tracking Operation

The reliability of the two trains during tracking operation is obtained through simulation shown in Figure 10. The reliability evaluation of the process is further carried out by using the above-mentioned reliability model. It can be seen from Fig. 10 that when the train 2 is tracking the train 1, due to the influence of external factors such as communication, the state adjustment will be delayed, which will lead to the fluctuation of the tracking speed. However, during the normal operation of the two trains, the fluctuation of the tracking state has little effect on the reliable operation of the two trains. When the front train brakes or even stops, if the following train does not brake in time or the braking is too slow, especially when the following vehicle cannot obtain the status of the preceding train in time due to communication delay, the reliability will drop sharply, affecting safe operation.

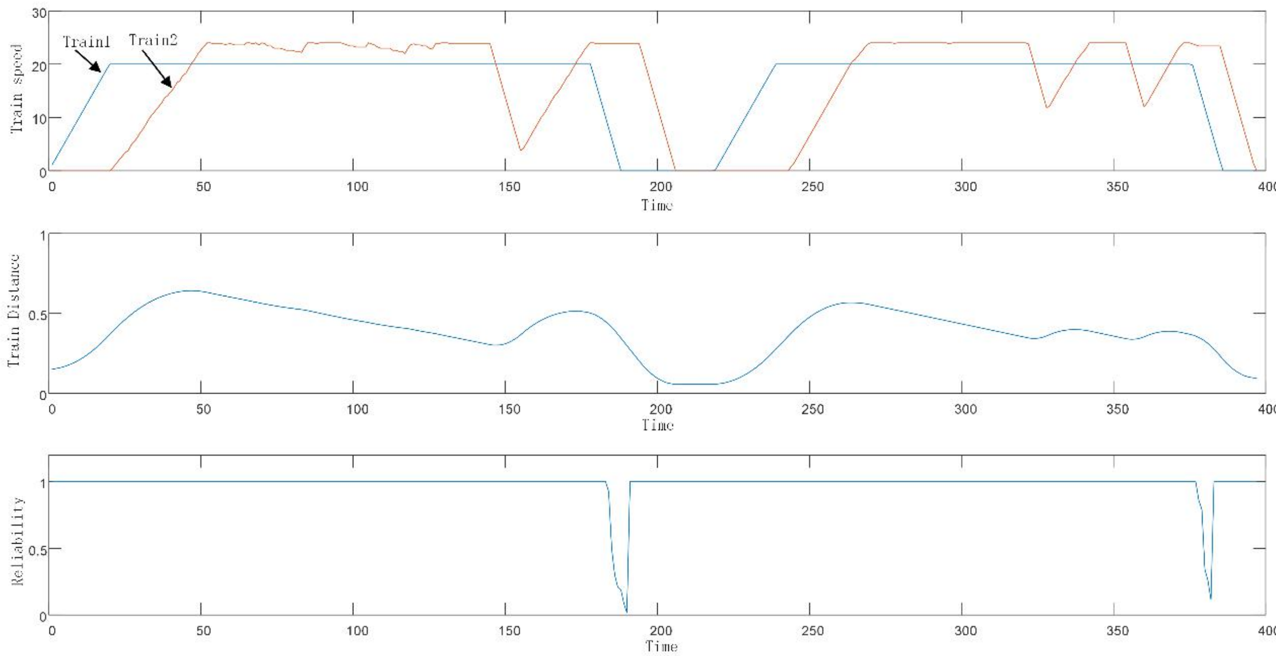

Fig.10 Real-time reliability evaluation of train operation

5. CONCLUSIONS

This work takes the reliability evaluation of train cooperative braking as the requirement. Starting from the safety conditions that should be met during the braking process of the train, the reliability of the two-train cooperative braking when the preceding train is at a standstill and at a constant speed are discussed separately, and a multi-train cooperative braking reliability evaluation model is established, and the key parameters affecting reliability are obtained. The influence of different parameter changes on the reliability of train cooperative braking is also studied. Finally, the reliability changes during the tracking operation of the two trains are evaluated. The research results show that the communication delay, driving distance, relative speed and braking performance determine the safety and efficiency of train operation during train braking. Among them, the communication delay has the greatest influence. The longer the communication delay, the lower the reliability. When the front vehicle brakes or even stops, if the following vehicle does not brake in time or the braking is too slow, especially when the following vehicle cannot obtain the status of the preceding vehicle in time due to communication delay, the reliability will drop sharply, affecting safe operation. Future work might focus on finding more suitable analysis methods and evaluation methods of train cooperative braking reliability analysis.

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