[DRAFT 2]

A Real-time Train Collision Incremental Pre-Warning System Based on Big Data Prognostics

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Abstract: Train control systems (CTS) and signaling systems are essential to ensure the safety and efficiency of train operations. Their operability is critically important to the overall safety and reliability of railway operations. In this paper, a Real-Time Train Collision Incremental Pre-warning System (hereafter RTCPS) based on Big Data Prognostics is proposed. RTCPS is intended to run alongside traditional CTS and automatic train protection (ATP) systems, performing monitoring in order to enhance safety and reliability.

Keywords: RTCPS; Train collision; Security monitoring; Real-time; Pre-Warning

1.Introduction

The speed and the frequency of train operations have increased rapidly in recent years. Meanwhile, the number of railway accidents has also increased rapidly[14], among which train collisions are the foremost cause of human and financial loss. The prevention of train collisions is accordingly a top priority for the railway industry.

One method is to use train control systems (CTS) and signaling systems, which improve the efficiency of train operations as well as monitoring their safety. Another is automatic train protection (ATP) systems.

However, failure in these systems can itself cause catastrophic railway accidents, such as the accident which happened in China on 23 July 2011: caused by a failure of signaling systems[15,16]. Failure in signaling or ATP may lead to safety deterioration and accident, and it is therefore necessary to supplement these systems with an improved train collision pre-warning system.

Considerable research in this field has been conducted in recent years. Germany began to develop a series of Railway Collision Avoidance Systems (RCAS) based on communication [5][6]. In turn, the India Railway Company developed the Anti-Collision Device Network [7][8], while Japan developed the Vehicle Approach Warning System in the Shinkansen[9]. In the UK Altran released the COMbined Position Alternative Signaling System (COMPASS) for train operations[10]. The Tracing and Approach Warning System for High-Speed Trains has been proposed by Cai Bai-gen[1][2]. The Interval Real-Time Warning System of Train Tracing has been proposed by Wang Junfeng[3]. In 2012, Beijing Zhongtietong Technology Development Center of Signal & Communication Co., Ltd tested their Train Interval Real-Time Tracing and Collision-Avoidance Warning System on the Qinhai-Tiben Railway[4].

In the infrastructure for train safety, satellite positioning and wireless communication are increasingly involved in addition to traditional signaling and ATP systems. The present paper proposes a Real-Time Train Collision Incremental Pre-Warning System (RTCPS) based on Big Data Prognostics, which runs alongside existing train control systems with the aim of safety enhancement. The paper forms part of our R&D project[18] and presents our proposed contribution to contemporary train collision prevention.

The rest of the paper is organized as follows. In section 2, the architecture and structure of the RTCPS are described. In section 3, we describe the principle of the RTCPS and give the details of a real-time prognostic algorithm based on available data sets. In sections 4, we evaluate the reliability and efficiency of the RTCPS.

2. The architecture of the RTCPS

This section describes the overall structure and architecture of the RTCPS.

2.1 The overall structure of RTCPS

RTCPS acquires operation data of existing in-service trains in real-time using individual data-collecting devices such as reliable GPS (Global Positioning Systems) and devices installed on the operating trains and tracks. TCS and ATP equipped with the RTCPS are shown in Fig.1. The safety-critical data used for RTCPS includes inputs from TCS systems and ATP systems[11].

The left part is the main portion of the extended function for monitoring the safety of the train. The RTCPS operates alongside existing train control systems, ATP systems and signalling systems to manage train operation safety. When the RTCPS identifies a potential hazard, the information will be displayed to the train controllers who can react to it and handle operating safety.

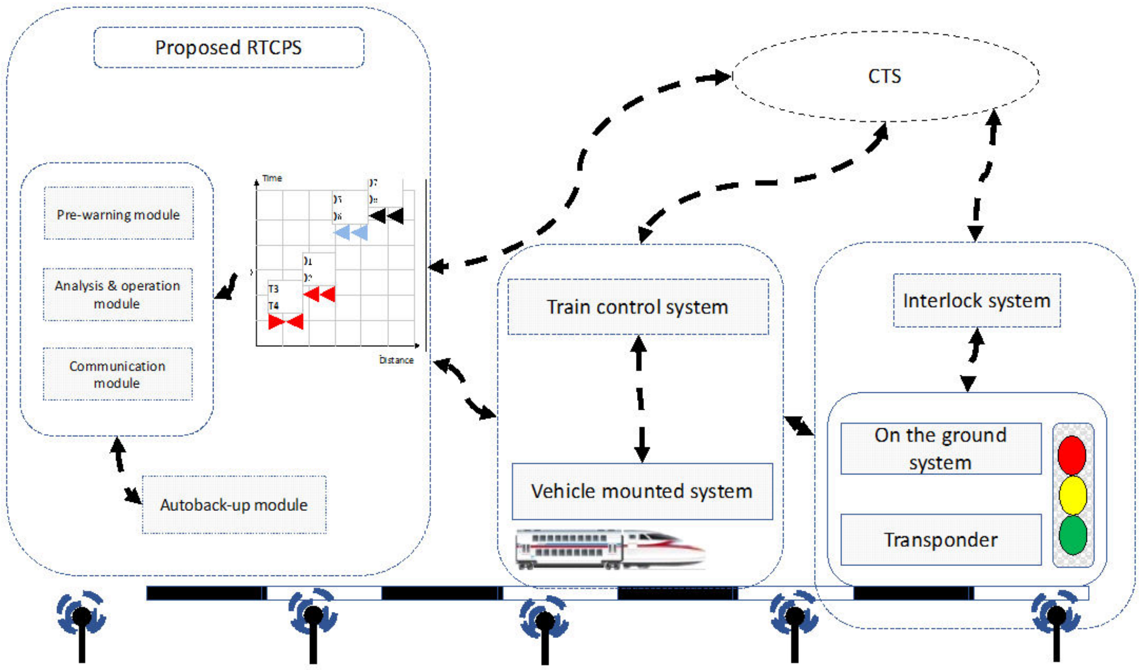

Fig. 1. The overall structure of RTCPS

2.2 The architecture of RTCPS

The structure of RTCPS is shown in Fig.2. It consists of five modules: Data Collecting Module, Data Analysis Module, Hazard Display and Interaction Module, Instruction Verification Module, and Big Data Storage Module.

The Data Collecting module acquires real-time operation data including velocity, position, distance of each train and other relevant safety critical data. The Data Process and Analysis module processes real-time operational data and analyzes the processed data to identify potential hazards.

The Display and Interaction Module displays potential hazard information including train collisions and gives multi-level incremental warnings to operators and train drivers.

The Instruction Verification Module verifies train control instructions (such as train slowdown instructions, acceleration instructions, etc.) of the monitored train.

The Big Data Storage Module automatically stores the real-time operation data and instruction logging Data and provides data supporting functions for train safety analysis.

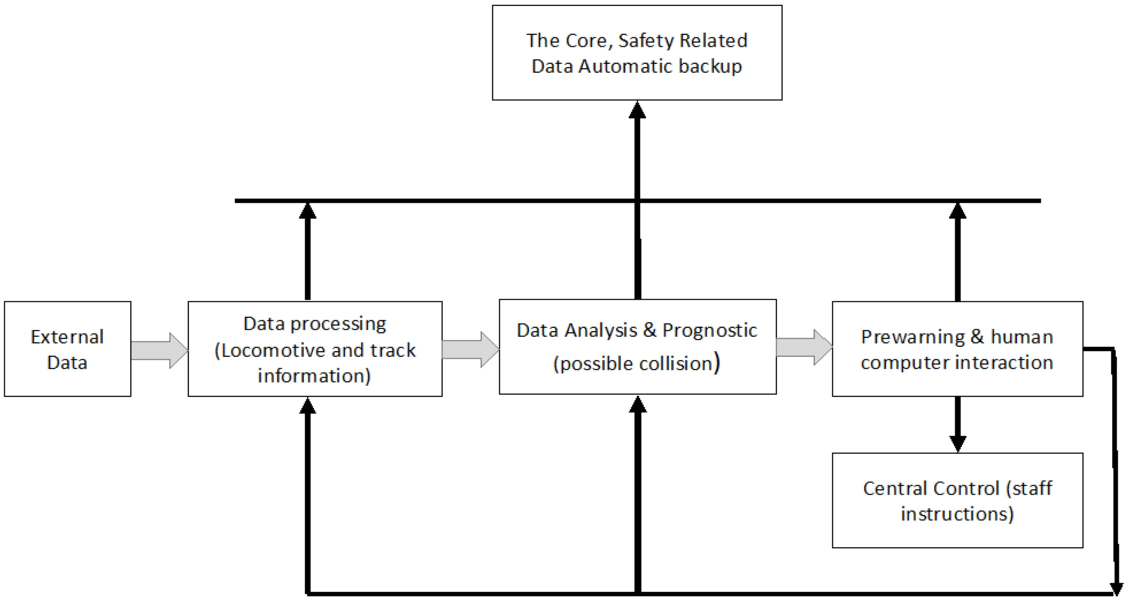

Fig. 2. The Structure of RTCPS

3. The Principle of the Pre-warning of the RTCPS

The principle of active system control and active system safety has been presented and published [17]. It assumes that the real time functioning of the system is accompanied by dynamic prognosis and diagnosis of the moving vehicle which identify the potential consequences of a problem and its probable source. The next step is to identify action to contain the problem and reduce its risk.

RTCPS thus uses **predictive simulation** to identify hazards, such as train collision, before they actually occur, using a combination of **stored data** (on previous conditions) and **real time data** (on current conditions). This data includes information about train speed, positioning, direction, and other conditions.

A key concept is that of the **train trajectory** (see below). These can be generated in a defined future time frame, stored, and used to identify potential train collisions. From these pre-generated **hypothetical** train trajectories, the possibility and probability of **actual** future train collisions can be estimated. Train and railway conditions are dynamic and can deteriorate at any time. RTCPS therefore makes essential use of both real time and stored data in its predictive estimation of hazards and hazard avoidance, where the predominant hazard is that of train collision.

3.1 The Definition of Train Trajectory

We suppose that RTCPS predicts train trajectories within the time Δt by arrival time and velocity. Here, trajectory prediction is merely based on real-time operation data, ignoring influences such as performance of train, track conditions and weather. The predicted trajectory of operation train set is defined in the formula (3-1):

① Train { i, $p_o(x_0, y_0), p_e(x_e, y_e), v_0$ } (3-1)

② $Si = v_0 * \Delta t$

Where: i, v_0 and p are respectively the unique number, instantaneous velocity and position of
this train;
The predicted trajectory of velocity v_0 is defined as ***Trajectory*** (p_o, p_e);
x and y are coordinate values of position p;
p_o is the current locomotive position,
p_e is the locomotive position after a period of time Δt.

Because of ***Si*** changed with velocity, acceleration and time, potential collision can be predicted by monitoring of ***Si***.

3.2 The Definition of Train Collisions

During the operation, trains will enter inevitably into a complex state or states (due to abnormal track conditions such as speed limit section, block section, site, fork and tunnel). And train collision mode includes encounter collision, rear-end collision, side collision and so on. In this paper, protection mode is discussed in the context of rear-end collision.

Consequently, protection mode is categorized into train collision pre-warning protection mode and safety point pre-warning protection mode, shown in Fig. 3 and Fig. 4 as follows.

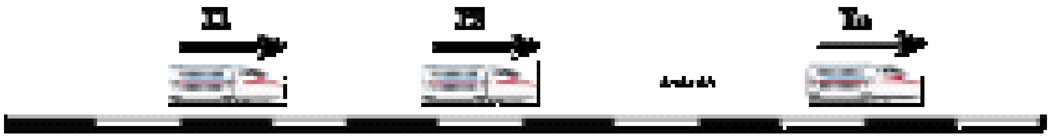

Fig.3. The railway status of the train rear-end collisions protection mode

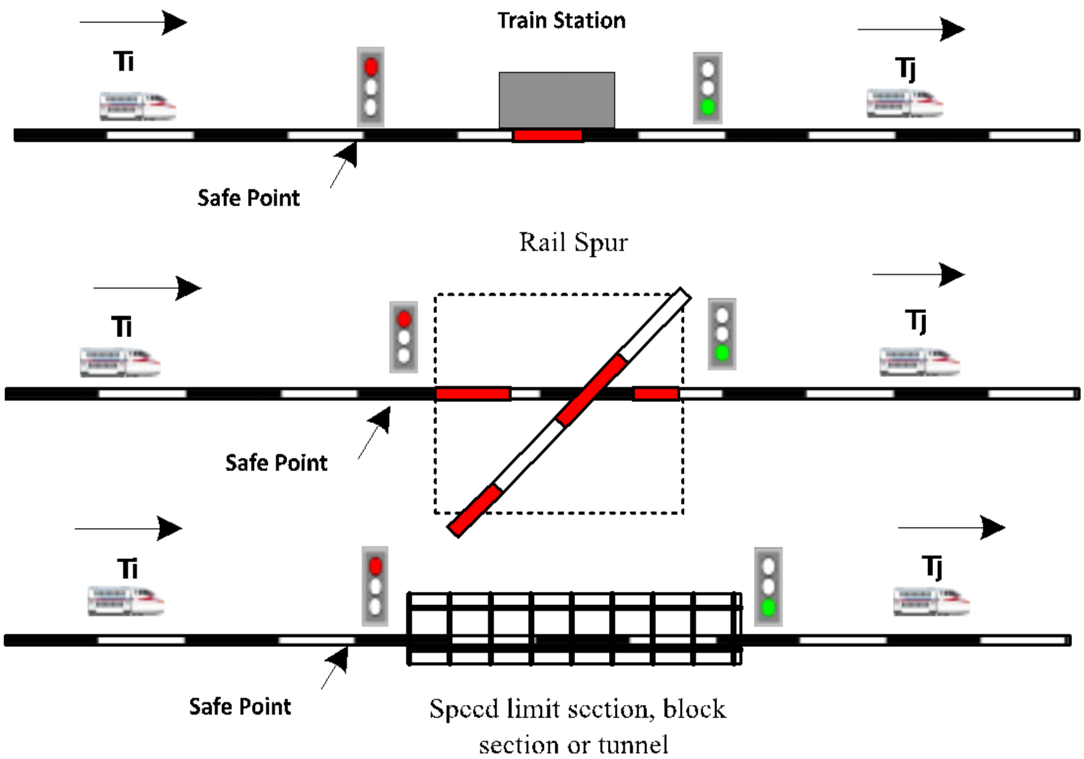

Fig. 4. The railway status of the safe point pre-warming protection mode

In the first case in Fig.4, we may note that two or more trains are running on the same track. There are no complex sections (abnormal track conditions such as speed limit section, block section, site, fork and tunnel) between any two trains.

The second case in Fig.4 shows that T2 is the nearest following train of T1, and there also exist complex sections between T2 and T1.

Considering both cases, trajectory-based RTCPS analysis identifies collision possibilities by acquiring real-time operation data on monitored trains and track conditions. Also, RTCPS offers protection and gives warnings using these two protection modes (M_collision and M_safety).

3.2.1 *Train collisions pre-warning protection mode* (M_ collision)

RTCPS monitors trains continuously or periodically, then it gives collision warnings by analyzing route planning and real-time operation data.

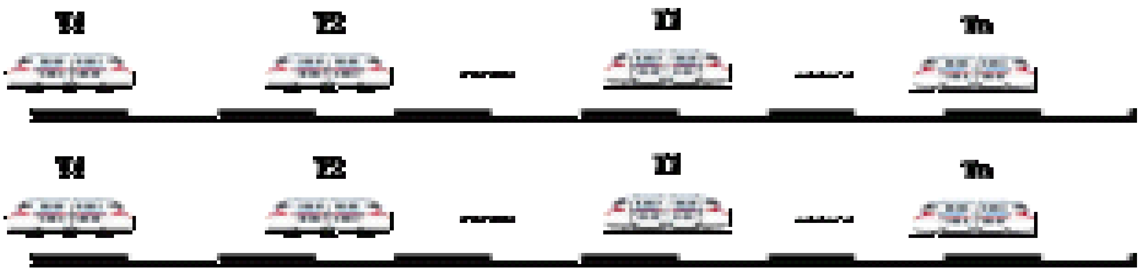

Fig. 5. The train set of the train collisions protection mode

Under the collision and analyzing mode, for the monitored operation trains $Train\_Set$, RTCPS will generate the trajectories for these trains. From these trajectories, we identify the trains that may collide, and output the train collisions represented by PTC_Set. Here the potential train collison set is formally defined by the formula 3-2. If the potential collisions meet certain specified conditions, then the collision relation between two trains is defined as 'true'. Combined with the graph above, the potential collisions are defined as follows.

① Train_Set = $\{ T_i \mid i \in N^* \}$

② PT _Set = $\{ <T_i, T_j> \mid i \neq j, \} T_i \in$ Train_Set, $T_j \in$ Train_Set $\}$

③ PTC _Set = $\{PT_{ij} < T_i, T_j > \mid PT_{ij} < T_i, T_j > \in$ PT_Set $\}$ (3-2)

Where T_i and T_j are the two moving trains, *Train_Set* denotes the set of all monitered trains, *PTC_Set* denotes the set of trains under the monitor of Collision Mode, PTC_Set denotes the set of train sets which contain potential collisions:

- If and only if trainset <Ti，Tj> belongs to PT_Set, the Collision Mode is applied.
- $PT_{ij} < T_i, T_j >$ denotes any one of the monitered train groups by Collision Mode, $PTC_{ij} < T_i, T_j >$ denotes one of the train groups posibilly collided.

If the collision relation for a pair of trains is 'true' in $PTC_{ij} < T_i, T_j >$, this means that collision may occur between the trains, thus a potential collision event $c_{ij} < T_i, T_j >$, is generated. At this moment, the system marks this pair of trains and monitors it based on the forecast line. Otherwise, the system does not mark it. The possible collision event is shown as follows：

Collision（c_no, c_type, $c_{ij} < T_i, T_j >$, S_{ij}, c_t_{ij}, W_{grade}） （3-3）

Where *c_no* is the ID number of collision, *c_type* is the type of collision, W_{grade} is the level of the potential collision, S_{ij} is the distance between the two trains, c_t_{ij} is the time lapse till the potential collision.

- c_type *c_type* includes opposite collision(oc) and rear-end collision(rc).
- The T_i and T_j in $c_{ij} < T_i , T_j >$ means the two trains moving within a distance,

Where the two trains move in the same direction, T_j denotes the train moving behind.

In addition, RTCPS adopts a multi-level pre-warning strategy. This raises efficiency, and collision caused by delayed reaction is prevented. RTCPS is divided into several levels, depending on the actual situation. In this paper, we divided the strategy into three levels as below:

$$W_{grade} (w_{primary}, w_{middle}, w_{emergency}) \quad (3\text{-}4)$$

At pre-warning levels W_{grade} has three time values ($T_{primary}$, T_{middle}, $T_{emergency}$), corresponding to different pre-waning levels, respectively. This aims to ensure that there is enough time to be guided to safety by the controllers after RTCPS discoveres a potential collision accident.

The $T_{primary}$ is set to 20 minutes in RTCPS (this being modulated according to the actual situation). Such a multi-level pre-warning system assists the controllers in providing timely responses to a potential collision scenarios. During this time, a hazard warning is issued to the TCS controller, then the staff of the CTC traffic center alter the train operations to prevent the accident.

For setting the time value T_{middle} and $T_{emergency}$, RTCPS chooses the time value of $4*T_{common\_brake}$ and $2*T_{common\_brake}$ respectively. T_{common_brake} denotes the time required to reduce train speed to a complete stop by common braking.

The rear-end collision is analyzed in detail below. (The opposing collision is in theory similar to the rear-end collision, and will not be discussed here.) The impact of different levels of events will also be evaluated and analyzed. In addition, we provide detailed descriptions of the pre-warning strategy.

(1) the rear-end collision

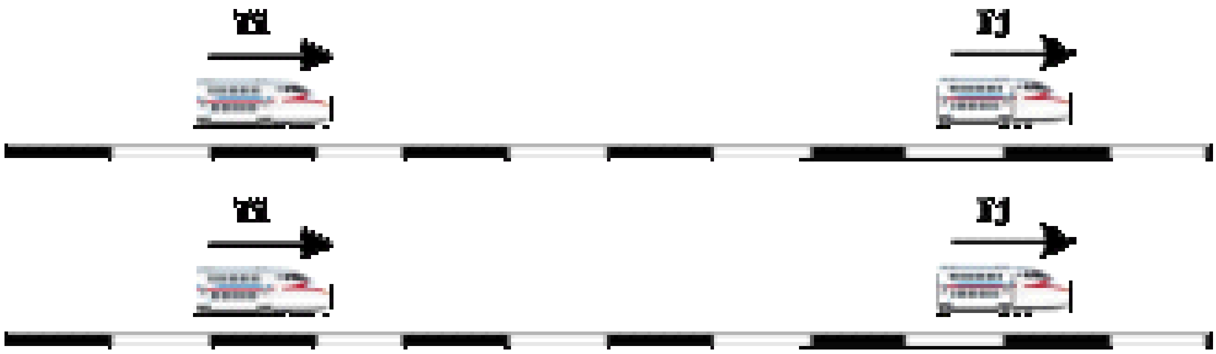

Fig. 6. Train-following model in the same track

The analysis of the train rear-end collision in Collision Mode is expressed as follows:

① $< T_i, T_j > \in PT\_Set$
② $c\_type = rc$
③ $v_i > v_j$ （3-5）

Where: *PT_Set* shows the set of train groups monitored by Collision Mode, *rc* indicates the mode of rear-end collision, *i* is the number of this train, while j stands for the train running forward. v_i and v_j is the speed of the trailing train and the forward train.

- Formula ① indicates the train trajectory and the situation of the track lines. T_i and T_j meets the condition for the group of trains which are monitored by Collision Mode.
- Formula ② indicates that the trains are running in the same direction. Under the rules of the "train control system overall technical program", there is always a settled train safety distance between two trains in train control systems. (The safety distance of the train is not simply the minimum tracking distance. In principle, it is about 60 meters when the trains are in the station and 110 meters when the trains are running).
- Consider equation ③, the speed of the running train is faster than the forward one. T_i and T_j are running at a current speed, respectively. When the distance between the head of the trailing train and the rear of the forward one is equal to safe distance after a period of time T, RTCPS predicts that rear-end collision may happen. When the operational status of the trains meets three conditions of formula 2-5 at the same time, the train group will be regarded as a potential collision accident of this train group, then we have:

$$\langle T_i, T_j \rangle \in R \subseteq Set \qquad (3\text{-}6)$$

When it is judged that there is a potential collision accident, the system will calculate the time c_t_{ij} for how long the collision will happen.

$$c\_t_{ij} = \frac{s_{ij} - L_{protect}}{v_i - v_j} \qquad (3\text{-}7)$$

Where: c_t_{ij} is the time lapse till the potential collision accident happens, $L_{protect}$ is the safety distance of this train, S_{ij} is the distance between the head of the train behind and the rear of the forward one in real-time.

Combining c_t_{ij} and S_{ij}, the system works out the emergency level of the potential collision and simultaneously generates multiple values.

The determined conditions of $W_{primary}$ is shown as follows,

① $S_{ij} - L_{protect} \geq v_{ij} T_{middle}$

② $T_{middle} < c\_t_{ij} \leq T_{primary}$ （3-8）

Where $T_{primary}$ is the time set by the primary pre-warning mode, and T_{middle} is the value of time which is set by intermediate pre-warning mode.

- Formula ① and ② is an AND relationship. It means that when ① and ② is met simultaneously, the system will generate a collision that the degree of urgency is primary. Primary pre-warning mode will be used and the staff will be warned. Hence, we have an expression of the primary pre-warning mode.
- Collision（c_no, rc, $C_{ij}\langle T_i, T_j \rangle$, S_{ij}, c_t_{ij}, $W_{primary}$） （3-9）
- The condition whether it's W_{middle} is shown as follows,

①$V_{ij} T_{emergency} \leq S_{ij} - L_{protect} \leq V_{ij} T_{middle}$

②$T_{emergency} < c_t_{ij} \leq T_{middle}$ （3-10）

- Formula ① and ② is a OR relationship. It means that as long as ① or ② is met, the system will generate a collision that the degree of urgency is intermediate.

Intermediate pre-warning mode will be used and the staff will be warned. Hence, we have an expression of the intermediate pre-warning mode.

- Collision（c_no，rc，$C_{ij}<T_i,T_j>$，S_{ij}，c_t_{ij}，w_{middle}）（3-11）

The determined conditions of $W_{emergency}$ is shown as follows,

①$S_{ij} - L_{pro} \leqslant T_{emergency}$

②$c_t_{ij} \leqslant T_{emergency}$ （3-12）

- Formula ① and ② is a OR relationship. It means that as long as ① or ② is met, the system will generate a collision that the degree of urgency is emergency. Emergency pre-warning mode will be used and the staff will be warned. Hence, we have an expression of the emergency pre-warning mode.

Collision（c_no，rc，$C_{ij}<T_i,T_j>$，S_{ij}，c_t_{ij}，$W_{emergency}$）（3-13）

(2) Pre-warning strategy

The following figure shows the schematic diagram of train collision pre-warning mode in RTCPS, for which $T_{\text{primary}} > T_{middle} > T_{emergency}$.

Fig.7. The schematic diagram of train collisions in RTCPS

The RTCPS system organises possible collisions in a hierarchical and incremental manner. System monitor the running trains, and when the predicted potential collision accidents meet the conditions of primary, middle and emergency pre-warning, the system will give different warning strategies based on the level of the pre-warning. Besides, the urgency of the collision determines how often the system refreshes: the higher the urgency, the more frequenet the system refresh.

- When the pre-warning is 'primary', icons displayed on the window are black, which suggests that the staff check the running status of the train group, and interact with other systems to avoid the accident;
- When the pre-warning is 'intermediate', icons are blue and alert tone will appear continuously, which inform the system staff to check the running status of the train group and inform the driver to notice the danger;
- When the pre-warning is 'emergency', with continuous sharp siren, the icons and the train alarm button displayed in red, this directly informs the driver to take the operation of train braking. If the distance between trains reaches common braking distance, the system will directly issue a directive of train braking, which will force the train's speed to reduce to a safe range.

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3.2.2 *Safety point pre-warning protection mode* (M_safety)

The track conditions may be complex, and may include such factors as rail spur and parking spots along the running way of trains, as shown in Figure 4. Usually, the train route in the turnout zone is controlled by the interlock system. RTCPS adopts the principles of train route control as well, and protects the safety of the train by setting safe points in front of special track sections.
We consider the mathematical model of security protection point pre-warning mode as follows:

① Safe_Point([illegible])
② SP_Set{SP_k | $k \in N$}
③ TSP_Set = {< T_i, SP_k > | $SP_k \in$ SP_Set} (3-14)

Where: i is the train number, k is the number of security points for the safety position, < T_i , SP_k> denotes that there is a forward point SP_k in front of T_i .

When there is a safety point in front of a running train, the system needs to check the state of the security point. If it is allowed for the train to pass, the system will use the train collision protection pre-warning mode to monitor the train, otherwise the system will combine the status of all the running trains and use security protection point pre-warning mode to monitor the trains.
At this moment, the system can calculate the time lapse till the train reaches the safety point by using current speed data:

$$TSP\_t_{ik} = \frac{S_{ik}}{v_i} \quad (3\text{-}15)$$

Where: S_{ik} is the real-time distance between the train Ti and the safety point. SPk, TSP_t_{ik} is the time that the train reaches the safety point with the current speed.

Since the danger level of M_safety is lower than Collision Mode, the system adopts two pre-warning modes of primary and emergency, in order to meet the high efficiency of transportation, ensure the train's running safety, and reduce the number of early warnings.

We consider the conditions of M_safety as follows:

$W_{primary}$: [illegible] $< TSP\_t_{ik} \leq 3*$ [illegible]

$W_{emergency}$: $TSP\_t_{ik} \leqslant$ [illegible] (3-16

When the distance between the train and the safety point equals the value of current speed multiplied by 3* [illegible], RTCPS enters primary pre-warning system mode, the icons flash yellow, and the staff will notify driver to check running state of the train.

When the distance between the train and safety point equals the value of current speed multiplied by [illegible], the warning button flashes yellow with a pre-warning tone. The warning signals and tones directly notify the train driver to check the train's running state and operate the train's braking system, in order to reduce the running speed to a permissible range.

Fig. 8. The schematic diagram of safety point pre-warning protection mode in RTCPS

4. Evaluation and efficiency of RTCPS

4.1 Analysis of Independence and Integrity

RTCPS is independent of the other train control system (TCS). Both its data sources and its principles of analysis and calculation are different from the train control systems. The data sources use an independent data acquisition module, and the forecast and analysis module adopts a calculation model which is different from the existing train control system (including the ATP system). RTCPS works in parallel with the other systems, which conforms to the principle of the independence of train control system.

RTCPS monitors the safety of the ATP system and communicates with other systems, which provide dispatching support for the scheduling control system. Hence, RTCPS can adjust a train's state by combining the whole pre-warning of potential collision accidents before the ATP system triggers braking systems. Therefore, the integrity principle of the train control system (TCS) is met by RTCPS.

4.2 Analysis of Safety

Introducing RTCPS running alongside existing TCS brings significant advantages to the safety of train operations as follows:

- RTCPS can supervise ATP systems at the system design level. Besides, the hierarchical organisation of warnings in RTCPS creates sufficient time for diverting trains into a safety state to avoid accidents.
- RTCPS analyzes, forecasts, and monitors the states of all trains in real-time, and so differs from an ATP system. An ATP system only concerns pairs of trains and calculates protection by the interval between them. RTCPS is more efficient than ATP systems at a global level, and more conducive to the scheduling of train control real-time optimization.
- RTCPS has independent data sources, which avoids the error of analysis and calculation caused by equipment failure of ATP. Hence, RTCPS can operate when the ATP system fails.
- Data sources of RTCPS are independent, also the analysis and calculation models are different between RTCPS and ATP systems, which may reduce the possibility of collision caused by a single system's fault.

- RTCPS runs alongside the ATP system, monitoring and providing warnings for train operations simultaneously, which means a dual protection for train set operation.
- RTCPS forecasts possible collisions in advance, and gives incremental warnings of potential collisions based on distance and time. This may improve customer experience, as an ATP system running alone could cause the emergency brake to be activated when the train is running at very high speed.

4.3 Analysis of Reliability

To analyze the reliability of RTCPS, we adopt the evaluation methodology found in existing literature [3]. Based on the train set on the Beijing-Shanghai high-speed railway, we analyze the reliability of RTCPS working in parallel with TCS. The figure below shows this reliability evaluating model.

Fig. 9. The diagram of parallel protection model of RTCPS and ATP system

Usually, reliability can be shown in terms of R(t). In a repairable system, R(t) is analyzed by the Mean Time Between Failure (MTBF) of this system: the higher the value of MTBF, the higher R(t) we have. Hence, the reliability of RTCPS can use the evaluation methodology of repairable systems, which can be evaluated using the following indicators: MTBF, Mean Time To Repair (MTTR), fault frequency (λ), maintenance rate（μ）, etc.

In repairable systems:

$$MTBF=1/\lambda \qquad (3\text{-}1)$$

$$MTTR=1/\mu \qquad (3\text{-}2)$$

By using a Markov model in the evaluation methodology of repairable system [3], we consider that if any component breaks down in a series structure, the other components will continue to complete the given function. Then we have:

$$MTBF=1/N*\lambda \qquad (3\text{-}3)$$

When the two different components work in parallel:

（3-4）

The reliability of the system has been calculated using data in existing literature [3]. As a result, when the equipment of the ATP system reaches SIL (Safety Integrity Level) grade 4, and the equipment of RTCPS reaches SIL2, then we have data correspondence as follows:

Table 1 Reliability indicator parameter evaluation list

	MTBF(h:)	λ	MTTR(h:)	μ
ATP	$1.0*10^{9}$	$1.0*10^{-9}$	0.1	10
RTCPS	$1.0*10^{7}$	$1.0*10^{-7}$	4	0.25

Nowadays, there are 36 pairs of trains running on the Beijing-Shanghai high-speed railway every day, so N is 72. According to formula (3-3) and the data above, we have:

For ATP system, $MTBF_{ATP}=1.389*10^{7}$, $\lambda_{ATP} = 7.2*10^{-8}$
For RTCPS, $MTBF_{RTCPS}=1.389*10^{5}$, $\lambda_{RTCPS} = 7.2*10^{-6}$

Due to the parallel work mode of RTCPS and ATP systems, by means of substituting the values calculated above into formula (3-4), we have:

$$MTBF_{parallel} = \frac{\mu_{ATP} * \mu_{RTCPS}}{\lambda_{ATP} * \lambda_{RTCPS} * (\mu_{ATP} + \mu_{RTCPS})} = 4.705*10^{11},$$

$$MTBF_{ATP}=1.389*10^{7}。$$

By comparison, the result shows that the MBTF increases from $1.389*10^{7}$ to $4.705*10^{11}$. Obviously, the reliability of the train has significantly improved. Therefore, after the introduction of RTCPS, the evaluated train operation factors show improvement. We have demonstrated as follows:

Table 2 Performance evaluation table of the RTCPS joined with the TCS

Performance assessment	Parallel protection model
Integrity	Enhanced
Independence	Same
Safety	Enhanced
Reliability	Enhanced

5. Summary

The RTCPS system provides supplemental safety protection for the hazard caused by failure of the train control system, the signal equipment, or ATP system. The RTCPS system makes use of safety-critical train operation data, analyzes this data set in real-time for potential hazards, and outputs identified hazards including potential train collisions.

Based on the reliability analysis above, if RTCPS runs alongside the train control system, the integrity, safety, and reliability of the train operations may be greatly improved.

Future work is planned to include hardware and software installation details for RTCPS, simulation experiments using actual train operation data, and a full intelligent train safety system based on real-time big data analysis of train operations.

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