This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

A New Early Warning Method of Train Tracking Interval Based on CTC

Junfeng Wang and Jungang Wang

***Abstract*—For railway operations worldwide, train rear-end collision accidents occasionally occur, resulting in heavy casualties and property loss. To avoid the occurrence of such incidents, a novel early warning method of train tracking interval based on centralized traffic control (CTC), or simply CTC interval prewarning, is proposed. When combined with the existing automatic train protection (ATP), the monitoring of train tracking interval is doubled. The proposed method calculates the minimum safety interval in real time and compares it with the actual spatial distance. When the actual spatial distance is less than the minimum safety interval, particularly when the ATP is at fault, the proposed method is capable of raising the alert and taking control measures to effectively avoid rear-end collision accidents. At the same time, this method displaces the manual supervision of train operation, thereby relieving labor intensity, and improves the effectiveness of supervision. This paper analyzes the necessity and feasibility of the proposed CTC interval prewarning method and explains the basic architecture of the system, data acquisition, tracking interval calculation, prewarning rules, and implementation. The CTC tracking interval calculation model has been established, and the table of warning distance of the different train speeds has been calculated. The reliability model of the train control system (TCS) has been established based on the CTC interval prewarning method, which is used to analyze the reliability and safety of the TCS.**

***Index Terms*—Centralized traffic control (CTC), fail-safe, high-speed railway, prewarning, tracking interval, train operation control.**

I. Introduction

TRAIN rear-end collision accidents are common in current global train operation systems. In existing train operations, the tracking interval distance between trains is monitored by automatic train protection (ATP) equipment. Should the signal equipment malfunction and the ATP fail to implement the "fail-safe" such that the train tracking interval is no longer monitored, the rear-end accident will not be averted. Train rear-end collisions occasionally occur both domestically and internationally. Such accidents account for the most significant proportion of all train-related incidents. The following illustrate several instances of train rear-end collision in China over the past few years:

- July 23, 2011: The electric multiple unit (EMU) train D301 experienced rear-end collision with the preceding EMU train D3115, between Yongjia Station and Wenzhou South Station on the Yongwen line. This resulted in a serious accident that brought a death toll of 40 people and left 172 people with injuries.
- July 31, 2005: The passenger train K127 from Xi'an to Changchun rear-ended the preceding freight train NO.3219, which led to the diversion of five carriages; six people in this accident died and 30 were injured.
- July 10, 1993: The passenger train NO.163 from Beijing to Chengdu rear-ended the preceding freight train NO.2011 between Xinxiang Station and Qiliying Station on the Beijing–Guangzhou line; 40 people died, and 48 people were injured.

  Similar railway accidents that have occurred overseas include the following:
- November 30, 2007: A passenger train experienced a rear-end collision with a freight train in Chicago, IL, which caused serious injuries to at least five people and slight injuries to dozens of others.
- July 13, 2005: A train stopped in Geteji of the Southern Sindh province in Pakistan was rear-ended by another train, which pushed several carriages into a diversion that, in turn, crashed with another oncoming train on a nearby rail, leading to the derailment of more carriages. The death toll was 150 with about 1000 injured.

The aforementioned accidents are merely the tip of the iceberg. The key to preventing train rear-end collisions primarily depends on the guaranteeing of interval distance between tracking trains [1]. The past contingencies illustrate that trains equipped with the ATP system or other monitoring systems are not guaranteed to avoid rear-end collision accidents. Therefore, it is important to present a method to avoid rear-end accidents in addition to the ATP. This paper proposes a prewarning method of tracking intervals based on centralized traffic control (CTC). This method and the ATP tracking intervals are parallel and work in tandem. Should the ATP equipment malfunction or output error messages, the CTC implements the "fail-safe" to ensure the safety of train operations. This method is an application and extension of the parallel control and management theory [2]–[5] in high-speed train control and security areas.

II. Necessity of Centralized Traffic Control Interval Prewarning

The signaling system of high-speed railways contains the train control system (TCS), the computer-based interlocking

Manuscript received December 20, 2011; revised May 17, 2012 and July 12, 2012; accepted September 10, 2012. This work was supported by the State Key Laboratory of Rail Traffic Control and Safety under Program RCS2011ZZ001. The Associate Editor for this paper was M. Á. Sotelo Vázquez.

J. Wang is with the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing 100044, China (e-mail: jfwang@bjtu.edu.cn; w2881@163.com).

J. Wang is with the Transportation Department, Beijing Railway Bureau, Beijing 100860, China (e-mail: bjwangjungang@126.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TITS.2012.2219528

system, the CTC, and other auxiliary signaling systems, such as the maintenance and monitoring system of the signals, the dynamic monitoring system of train control equipment, the train number tracking and wireless check system, the wireless transmission system of the dispatching command, the power system, etc. ATP is the main equipment of the TCS.

The tracking interval is the distance between the following train and the preceding train. The minimum safety interval allows for the safe operation of the train and the driver's comfort, with reference to the minimum distance between trains.

The tracking interval directly effects train passing capacity and operation security. The main factors that determine the minimum safety interval include train speed, the added distance during the time elapsing between the train control response and the driver's confirmation signal, the full braking distance of the train, the distance required for safeguarding against the errors generated from equipment and operators, the comfort and safety of driving distance, the length of the train, the restrictive speed of the track switch, the length of the station throat, the time of the transaction of the station operations, the efficient length of the main rails in station, etc. When the tracking interval distance is less than the train emergency braking distance, rear-end accidents will occur. To prevent train rear-end collision, the major expectation is not only to ensure safe distances between the neighboring trains [6].

In the high-speed railway signaling system, the necessity of design of the CTC interval prewarning system includes the following:

1) The signaling system of the high-speed railway is an integration of all the signaling equipment, subsystems, and auxiliary equipment. The integration of the systems is one of the key technologies of the signaling system of the high-speed railway; it plays a very important role in maintaining the safety of the signaling system. The TCS Functional Requirements Specification, TCS System Requirements Specification, and TCS Form-Fit Functional Interface Specification are the main reference sources for the integration of the systems [7]. Currently, the integration of the signaling system of the high-speed railway focuses on the interface technology between different equipment and subsystems, and the various line interconnection and intercommunications when the signaling equipment, which is provided by different manufacturers, combines into a single system. These signaling equipment and subsystems are developed at different times while they are added into the entire signaling system. Logically, the integrated signaling system, which is made this way, is not entirely designed in accordance with the system engineering theory; it can hardly play on the advantages of the system as a whole or operate at its level. The simplified addition entailed by integration lacks the sharing and fusion of the system information, possesses inadequacies of intersupervision and warning between the subsystems, and demonstrates an absence of the realization of the "fail-safe" design on the level of the system as a whole [8].
2) In the existing signaling system, ATP is used only to control the tracking interval and train speed. At times, the ATP cannot calculate or output the mistakes of the tracking interval and safety distance of braking, which are caused by failure of the signaling equipment, errors in signaling acquisition and transmission, and other interference; all of these impact the safety of the train operation. Therefore, it could more readily lead to accidents when the trains operate under the instructions that are calculated and output by ATP solely, without further supervision. Particularly in situations of contingency, there exist uncertain and dangerous elements in the instructions that are calculated and output by the ATP. Therefore, it is necessary to set up an additional means to supervise the ATP [9].
3) There are limitations to the ability of train dispatchers to take responsibility for auxiliary supervision. The dispatchers should apply the CTC to additionally supervise train operation and signaling equipment from the screen or monitors, including train tracking, train position and operation speed, signal status, train route, section blocking, etc. Given the speed of the trains and abundance of signaling equipment that has been installed, the contents that are displayed on the screens need to be changed. The dispatchers are not able to promptly respond. In addition, visual fatigue is caused by prolonged periods spent watching the monitors. All of these factors make it impossible to supervise the train operation by manpower alone [10].

III. Structure of Centralized Traffic Control Interval Prewarning System

ATP interval control already exists, but CTC interval prewarning is newly proposed, which is achieved based on the existing CTC system. In the CTC interval prewarning system, for hardware, only one application server is added, and other hardware is sharing with the existing CTC equipment. For software, the functions of data acquisition, interval calculation, prewarning output, and so on, are added. The purpose of these is to render the CTC interval prewarning method simple for implementation with for cost and independent of ATP interval control.

A. Overview of CTC System

The CTC system is the technical equipment used to centralize the control of the signal equipment and to command and manage train operations directly. The CTC system is a highly automatized system of dispatching and control. It adopts the design principle of decentralized and autonomous intelligence, centers upon the adjustment of train operation scheduling and control, and gives consideration to train operation and shunting service [11]. For example, in China, the line from Beijing to Shanghai has a length of 1380 km, and CTC monitors 72 pairs of trains daily.

The CTC system consists of three subsystem as follows.

1) Dispatching Center Subsystem: The core of CTC, i.e., the so-called dispatching center subsystem, which operates

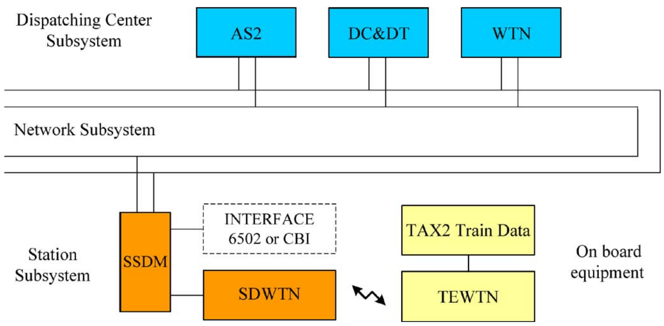

Fig. 1. Structure of the CTC interval prewarning system.

between the dispatching center and between stations, performs many functions, such as monitoring the train position within the control zone, commanding the train operation, establishing and adjusting the train operation schedule, transmitting dispatching orders, exchanging messages with the dispatcher workstation in adjacent sections, making the plan for the shunting works, and adjusting and commanding the unmanned stations.

2) Station Subsystem: The Station Self-Discipline Machine (SSDM) is the key equipment of the CTC that should meet the functional requirements as follows: Receive the adjustment schedule of the train operation delivered by the dispatching center and the instructions from the dispatching center or the station operator on duty, deliver the information to the interlocking system for execution in due time after a testing result of no conflict, receive signaling equipment status express information, track train number, collect train actual operation data in real time and upload which to the dispatching center, hold the condition of the implementation by the interlocking system and adjust the train route according to the feedback, and receive information concerning the condition of the equipment and the actual operation map of the two neighboring stations.

3) Network Subsystem: The network subsystem is the tie connecting the dispatching center subsystem and the station subsystem. The network communication equipment and passageway of transmission attribute to the double-loop network, which improve reliability by adopting the means of circuitous rings and redundancy.

B. Parts of CTC Interval Prewarning

The CTC interval prewarning system consists of the existing Wireless Train Number (WTN) unit, Dispatching Command and Dispatching Telephone (DC&DT), Train onboard Encoding of Wireless Train Number (TEWTN) unit, Station Decoding of Wireless Train Number (SDWTN) unit, train data acquisition unit of TAX2, and the newly added Application Sever 2 (AS2). Fig. 1 refers to the structure of the CTC interval prewarning system.

As the number of trains is high and their speed considerable, whereas the calculation of tracking intervals is a heavy task, and real time carries a high requirement, AS2 is added to the CTC dispatch center subsystem to calculate the train tracking interval; the WTN unit is used to acquire the necessary data, and the DC&DT is used for the output of train tracking interval overrun warnings.

The working principle of CTC interval prewarning is that AS2 calculates train tracking interval distance according to the traction calculation, using the data of the train's speed, acceleration, and position information from WTN. If the actual spacing distance is less than the minimum safety interval, a shortened movement authority (MA) is output, or DC&DT is used to order the driver to slow down or stop the train.

IV. Method of the Centralized Traffic Control Interval Prewarning

The CTC interval prewarning and ATP tracking interval control are working together, and CTC monitors the output of ATP tracking interval control. When ATP failure leads to loss of control, the lack of control is filled by CTC. The CTC interval prewarning implements the prewarning and "fail-safe" measure to prevent rear-end train collision.

The CTC system assembles the core data of the operation dispatch, interlocking, and train control, which can meet the calculation demands of train tracking interval prewarning together. The CTC system is the upper layer of the interlocking and train control, which can control and command the signal equipment in station and section and in trains. CTC can control all trains on line. Using CTC as the carrier, all trains on line as the control objects, which makes it possible to set up real-time monitoring tracking interval and prewarning when the actual spacing distance is less than the minimum safety interval.

A. Data Acquisition

The calculation of CTC interval prewarning requires both dynamic and static data.

1) Dynamic Data Acquisition: The wireless train number onboard encoder will continue to encode information using the train number, locomotive number, running speed, train position, and the total weight and length of vehicles from the locomotive safety information test equipment (TAX-2) before the information will be transmitted to SDWTN although wireless. The received information is decoded by SDWTN and is sent to the CTC central server through the network subsystem. In practical applications, to further improve the reliability and real time of information transmission, train data are directly sent to the CTC center from the train through the GSM-R wireless channel.

2) Static Data Acquisition: Static data include line parameters and a part of the train data (e.g., brake ratio, train marshaling, etc.), which have been stored beforehand in AS2.

The train number is not only the core of train control and dispatching command but the key to the CTC interval prewarning system's obtainment of reliable data as well. The train number's accuracy is ensured by the train number tracking unit and the wireless checking system [12], [13].

B. Interval Calculation Model

The train operation distance and time are calculated by the following formulas [14]:

$$\Delta s = \frac{1000 \cdot (1+r) \cdot \left(v_2^2 - v_1^2\right)}{25.92 \cdot g \cdot c}(\mathrm{m}) \tag{1}$$

$$\Delta t = \frac{1000 \cdot (1+r) \cdot \left(v_2^2 - v_1^2\right)}{3.6 \cdot g \cdot c}(\mathrm{s}) \tag{2}$$

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

where

Δs and Δt operation distance increment and operation time, respectively, which are produced when the speed changes from v_1 to v_2;
c unit resultant force (N/kN);
r rotary quality coefficient, i.e., the ratio of the train rotary quality to the entire weight of the train;
g gravity acceleration, 9.81 m/s^2.

The unit resultant force c in (1) and (2) is necessary to consider the resistance of the train operation, the ramp, the curve, etc. All variations of the resistance are calculated as the regulations of *the regulations of the train traction calculation*.

The brakes of EMU adopt the comprehensive methods of braking. In current situations, special information on the brakes of EMU does not provide the brake force of EMU under the varying speeds directly; some parameters of the braking distance computation formulas are uncertain, and we cannot apply the existing braking distance computation formula mechanically. We can only apply the formula of the movement based on average speed to calculate the brake distance L_z of EMU, according to the braking deceleration a_z. Thus

$$L_z = L_k + L_e = \frac{v_0 \cdot t_k}{3.6} + 0.0386 \sum \frac{v_1^2 - v_2^2}{a_z} (\text{m}) \quad (3)$$

$$a_z = \frac{(b + w_0 + i_j) \cdot g \cdot 10^{-3}}{1 + \gamma} (\text{m/s}^2) \quad (4)$$

where

L_k braking vacancy distance (m);
L_e effective braking distance (m);
v_0 braking initial velocity (km/h);
t_k vacancy time (s);
b unit braking force (N/kN);
w_0 unit basic resistance of operation (N/kN);
i_j unit resistance of gradient (including curve conversion) (N/kN).

C. Tracking Interval Calculation of ATP

By adopting the target distance–speed curve, ATP monitors the train operation, as shown in Fig. 2(a). According to the four categories of the statistics of train control, they are named as MA, line description, temporary speed restriction, and train parameters. ATP calculates the permitted speed and target distance–speed monitoring curve. If the actual speed is beyond the limitation of the permitted speed, i.e., beyond the monitor curve, the ATP will give the brake information.

The target point of the following train ATP1 is the entrance T of the block section that the preceding train occupied; the target distance is the length that ranges from point T after leaving the protective distance to the train front.

Normal and comfortable driver operations are guaranteed by the train tracking interval in the line that is the distance L_{XATP} between the two trains preceding and following, i.e., the length of the train; the length of the block section; protective distance; the train braking distance; the confirmation of the driver; and

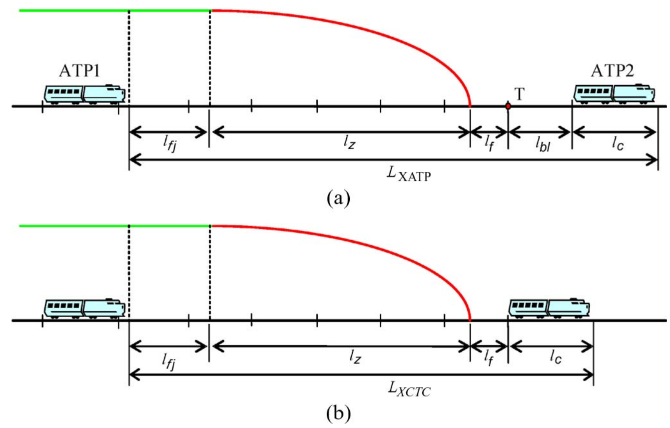

Fig. 2. Sketch of CTC and ATP tracking interval computing methods.

the distance of the train when the equipment delays its action, which, as a whole, is comprised of L_{XATP}. Thus

$$L_{\text{XATP}} = t_{fj} \cdot v_0/3.6 + l_z + l_f + l_{bl} + l_c + l_s (\text{m}) \quad (5)$$

where

t_{fj} additional time, including the response time of the signal system and the time of the driver confirmation of target distance and speed (s);
v_0 initial speed of the following train (km/h);
l_z length of the curve zone of the braking, which is formed by the vehicle ATP (m);
l_f protective distance (m);
l_{bl} length of the block section (m);
l_c length of the train (m);
l_s added length for driving comfort (m).

$$l_s = \frac{v_0 \cdot l_{bl}}{350} (\text{m}). \quad (6)$$

If the train is on the tracking movement, either entering or exiting the station, the distance caused by the delay of the train route transaction has to be taken into consideration to calculate the tracking interval.

D. Tracking Interval Calculation of CTC

The differences between the calculation of the tracking interval in CTC and ATP are as follows.

a) The statistics of the CTC calculation of the tracking interval are from the train, whereas the statistics of ATP are derived from the ground equipment of the track circuit, the transponder, the Train Control Center (TCC) of the station, or the Radio Blocking Center.
b) The CTC understands the position, speed, and acceleration of all the trains on a given line, whereas ATP only acknowledges the position, speed, and acceleration of a single train.
c) The tracking target of the CTC is the rear of the preceding train, and the tracking target of ATP is the entrance of the track circuit, which is occupied by the preceding train.

Therefore, the CTC calculation of the tracking interval is in terms of the movement blocking system rather than the length

TABLE I
VALUE OF WARNING DISTANCE OF THE TRAIN TRACKING INTERVAL ON FLAT AND STRAIGHT LINE

Speed (km/h)	Unit basic resistance w_0 (N/kN)	Braking deceleration a (m/s²)	Emergency braking distance (m)	L_{XCTC} (m)	L_X (m)	Speed (km/h)	Unit basic resistance w_0 (N/kN)	Braking deceleration a (m/s²)	Emergency braking distance (m)	L_{XCTC} (m)	L_X (m)
350	20.64	0.98	5498	11476	13421	200	7.86	0.86	1961	6457	7568
345	20.11	0.97	5358	11287	13204	195	7.54	0.86	1870	6317	7400
340	19.59	0.97	5220	11099	12988	190	7.23	0.86	1781	6178	7234
……						……					
300	15.68	0.93	4161	9645	11312	160	5.52	0.84	1289	5389	6278
295	15.22	0.93	4035	9470	11109	155	5.25	0.84	1214	5265	6126
290	14.77	0.93	3911	9296	10907	150	5	0.84	1141	5143	5976
……						……					
250	11.42	0.90	2974	7965	9354	60	1.62	0.81	206	3319	3652
245	11.03	0.89	2865	7806	9167	55	1.49	0.81	176	3239	3545
240	10.65	0.89	2757	7649	8982	50	1.38	0.81	148	3162	3440

of the block section. The distance tracking interval is calculated by CTC, as shown in Fig. 2(b). Thus

$$L_{\text{XCTC}} = t_{fj} \cdot v_0/3.6 + l_z + l_f + l_c + l_s(\text{m}). \tag{7}$$

The service brake mode curve and the emergency brake mode curve are used to calculate the tracking interval distances of EMU at the speed of 350 km/h, taking manned operations as the premise. The technical parameters are as follows.

a) The brake rate of the service brake curve is 0.8, the brake rate of the emergency brake is 1.0, and the brake rate of the station entrance is 0.5.
b) The pure air urgent brake distance of EMU at the speed of 350 km/h is within 5.5 km.
c) The length of the blocking section is 2000 m.
d) The formula of the unit operation basic resistance of EMU is $\omega_0 = 0.62 + 0.0082v + 0.00014v^2$ (N/kN).
e) The time of braking vacancy distance in emergency braking and in service braking is 2.0 and 1.5 s, respectively.
f) The whole weight of the train is 960 t, the quantity of the train unit is 16, and the length of the train is 410 m.
g) The brake deceleration of the train mode curve is 0.8 m/s.
h) The average deceleration of the train on the flat rail is 0.6 m/s.
i) The margin of error for both train speed and distance is 2%, the maximum length of the train protection distance at the station is 60 m, and the length in the section is 110 m.
j) Under the previous mode of the manpower, the additional time is $t = 4.3$ (leisure track inspection) $+$ 1.0 (response time of TCC) $+$ 3.6 (response time of the onboard equipment) $+$ 6.0 (time of the driver's confirmation of the signal) $=$ 14.9 s, which is rounded up to 15.0 s.
k) The delivery time $t = 4.3$ (leisure track inspection) $+$ 3.0 (delay of the unlocking) $+$ 3.0 (CTC confirmation) $+$ 13.0 (route transaction) $=$ 23.3 s, which is rounded up to 24.0 s.
l) The arrival working time $t = 3.0$ (delay of the unlocking) $+$ 3.0 (CTC confirmation) $+$ 13.0 (route transaction) $+$ 4.3 (response time of the track circuit) $+$ 3.6 (transmission from ground to vehicle) $=$ 26.9 s, which is rounded up to 27.0 s.

When the train runs on flat ground in a straight line without additional resistance supplied by a ramp, we can plug the parameters into (3), (4) and (6)–(8) to generate the warning distance of the train tracking interval, as shown in Table I.

E. Output of CTC Interval Warning

The purpose of the CTC warning is to monitor whether the train tracking interval controlled by ATP is within the safe stopping distance or not and to ensure the train's safety, particularly when ATP goes wrong or outputs error information. This approach of utilizing equipment instead of manpower to supervise the safety of trains on the rail lines would significantly improve the efficiency of the dispatcher.

1) Warning Output: The distance between two tracking trains is denoted by S. The distance between two tracking trains at the warning output of the CTC interval prewarning system is named L_X, which includes the distance of action response to warning. It is L_X but not L_{XCTC}. L_X is longer than L_{XCTC}. Thus

$$L_X = (t_{fj} + t_o) \cdot v_0/3.6 + l_z + l_f + l_{bl} + l_c + l_s(\text{m}) \tag{8}$$

where t_o is the time needed by the dispatcher to connect with the driver; it is provisionally set at 20 s.

The regulation of warning output is as follows:

a) When $S < L_{\text{XCTC}}$ and $v_0 \geq 45$ km/h are all satisfied, both warning and control are output by the CTC interval prewarning system.
b) When $v_1 \leq 45$ km/h, only the warning is output.

When we calculate L_{XCTC} using the statistics of chart 1, we should consider the changes caused by some factors, such as the line slope, curves, tunnels, etc.

2) Execution of the Warning: The dispatcher confirms the warning signal upon receipt and then makes two measures: One is outputting a shortened MA; second is getting in touch with the driver through DC&DT-based GSM-R, forcing the train to slow down or stop.

V. SAFETY ANALYSIS

CTC and ATP form the dual control in the structure. CTC interval prewarning plays a supervisory role, whereas ATP controls the train tracking interval, which improves overall security.

A. System Safety Used CTC Interval Prewarning

a) The CTC interval prewarning method enhances the safety of the train control at the level of the system overall. The CTC connects with the based interlocking and the TCS, which is regarded as the decision-making layer of the railway signaling.

b) The CTC generates the tracking interval between different trains on entire lines, whereas ATP only tells the tracking interval between the trains. CTC possesses more complete information than does the ATP.

c) The CTC and the ATP calculate the train tracking interval jointly. The CTC monitors control of ATP to the trains, which doubles the safety of the train control.

d) The source of CTC information differs from that of ATP. The independent calculation process avoids errors from common causes.

e) CTC train tracking warning achieves the system-level fail-safe. As complement to the fail-safe on the level of the signal equipment, they jointly strengthen the safety of the system.

B. Reliability Calculation

The safety of the signaling system is guaranteed by reliability. Under the stipulated time and conditions, the ability to complete the stipulated functions is called system reliability. The reliability indexes for the repairable system are as follows: reliability $R(t)$, availability $A(t)$, mean time between failure (MTBF), mean time to repair (MTTR), etc. [15]. Thus

$$\text{MTBF} = \int_0^{+\infty} R(t)dt \text{ (h)}. \tag{9}$$

When the Markov process is applied to describe a repairable system, we may deduce two situations as follows:

a) N identical components in series, i.e.,

$$\text{MTBF} = \frac{1}{N\lambda} \text{ (h)}. \tag{10}$$

b) Two different components in parallel, i.e.,

$$\text{MTBF} \approx \frac{\mu_1\mu_2}{\lambda_1\lambda_2(\mu_1+\mu_2)} \text{ (h)}. \tag{11}$$

The data of the high-speed railway signaling from Beijing to Shanghai are employed below. This line operates 72 couples EMU daily; the reliability model of ATP and CTC tracking interval computing hardware is shown in Fig. 3. CT is the statistics acquisition equipment and the wireless module, which are installed on every train, serving to collect statistics and transmit them to CTC.

In the mode: $n = 144$

ATP equipment reaches SIL4, hence

$$\text{MTBF} = 1.0 \times 10^9 \text{ in ATP, i.e., } \lambda = 1.0 \times 10^{-9}$$

$$\text{MTTR} = 0.1 \text{ h in ATP, i.e., } \mu = 10.$$

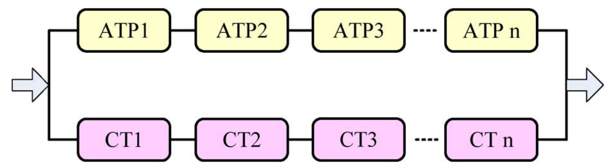

Fig. 3. Reliable hardware model of the system using CTC interval prewarning.

The reliability of the CT unit is lower than that of ATP, reaching SIL2, hence

$$\text{MTBF} = 1.0 \times 10^7 \text{ in CT, i.e., } \lambda = 1.0 \times 10^{-7}$$

$$\text{MTTR} = 4 \text{ h in CT, i.e., } \mu = 0.25.$$

Put these statistics into (10), i.e.,

ATP1, ATP2, ..., ATP144 in series connection

$$\lambda_1 = 1.44 \times 10^{-7} \qquad \mu_1 = 10$$

$$\text{MTBF} = 6.94 \times 10^6$$

CT1, CT2, ..., CT144 in parallel connection

$$\lambda_2 = 1.44 \times 10^{-5} \qquad \mu_2 = 0.25$$

$$\text{MTBF} = 6.94 \times 10^4.$$

Put these statistics into (11), i.e.,

$$\text{MTBF} = 1.176 \times 10^{11}$$

As a result, the MTBF increases to over 1.69×10^4 times by using CTC interval prewarning.

VI. Conclusion

The method of CTC train tracking interval prewarning is designed on the basis of the existing CTC system, and the hardware, with the exception of the newly added AS2, and all other equipment and networks are shared with the existing CTC. Hence, the achievement of this method is greatly facilitated, and the obtainment of statistics collection, tracking interval calculation, warning output, and warning action is made feasible. In tandem with the existing ATP train tracking interval control, this method doubles the safety of the monitor to effectively avert accidents of train rear-end collision. Train safety is quantified with the CTC real-time supervision of tracking interval control; it becomes indispensable particularly in situations of contingency involving either ATP equipment malfunction or output error. The reliability of the system is improved 1.69×10^4 times, after adopting the CTC interval prewarning method, in lieu of supervision of train operation by manpower; moreover, it increases working efficiency. The author proposes an approach to improve the efficiency of supervision in this respect.

Acknowledgment

The authors would like to thank Jenny, a graduate student at New York University, for assisting in proofreading.

REFERENCES

[1] C.-S. Hsu, C. Wang, and L.-K. Yang, “Onboard measurement and warning module for irregular vehicle behavior,” *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 3, pp. 501–513, Sep. 2008.

[2] F. Y. Wang, “Parallel control and management for intelligent transportation system: Concepts, architectures, and applications,” *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 630–638, Sep. 2010.

[3] F. Y. Wang, “Parallel system methods for management and control of complex systems,” *Control Decis.*, vol. 19, no. 5, pp. 485–489, 2004.

[4] B. Ning, T. Tang, H. Dong, D. Wen, D. Liu, S. Gao, and J. Wang, “An introduction to parallel control and management for high-speed railway systems,” *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1473–1483, Dec. 2011.

[5] Q. Song, Y.-D. Song, T. Tang, and B. Ning, “Computationally inexpensive tracking control of high-speed trains with traction/braking saturation,” *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1116–1125, Dec. 2011.

[6] J.-F. Wang, “CTCS-2I: A new train control system suitable for trains with speeds up to 350 km/h,” *J. Transp. Eng.*, vol. 137, no. 5, pp. 327–332, May 2011.

[7] Sci. Technol. Div. Ministry Railways, System Requirements Specification (SRS) of CTCS-3 Train Control System (V1.0), Beijing, China: China Railway, 2009.

[8] J. Wang and Z. Lin, “Research on intelligent control strategy used in CTCS-3 train control system,” in *Proc. IEEE ICIRT*, Beijing, China, Jul. 10–12, 2011, pp. 447–450.

[9] X. Wang, *Intelligent Railway Transport System ITS-R*. Beijing, China: China Railway, 2004.

[10] W. Huang and X. Ji, “Several crucial techniques for the high speed adaptability of CTCS-3 train control onboard equipment,” *China Railway Sci.*, vol. 3l, no. 3, pp. 87–92, Mar. 2010.

[11] Sci. Technol. Transp., no. 15 The Distributed Autonomic Centralized Traffic Control System (CTC) Technology Conditions (Interim) [S], Beijing, China: China Railway, 2004, no. 15.

[12] X.-J. Wang, “Research on train number technique for decentralization-and-self-regulation centralized traffic control system,” *Railway Comput. Appl.*, no. 11, pp. 42–45, 2008.

[13] L. Liu, D. Wei, Y. Yin, and F. Wei, “Mechanism and calculation of speed-interval control of high-speed passenger trains,” *J. Southwest Jiaotong Univ.*, vol. 41, no. 5, pp. 575–581, 2006.

[14] S.-G. Zhang, *Technical of Plan CTCS Leve3 Train Control System*. Beijing, China: China Railway, 2008.

[15] J. Wang, X. Wang, and H. Zhao, “Safety analysis on the train running control system in Qinghai–Tibet railway,” *China Saf. Sci. J.*, no. 11, pp. 52–57, May 2001.

Junfeng Wang received the Ph.D. degree from Beijing Jiaotong University, Beijing, China, in 2002.

He is currently an Associate Professor with and the Vice Director of the State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University. He has participated in several major projects on high-speed trains funded by the Chinese government. His research interests include intelligent transportation systems, communication-based train control, radio-based cab signaling, fault diagnosis, system reliability and safety, system-level fail-safe, and mutual-discipline control studies on high-speed railway signaling systems.

Jungang Wang received the M.S. degree from Lanzhou Jiaotong College, Lanzhou, China, in 1998.

He is currently with the Transportation Department, Beijing Railway Bureau, Beijing, China. He has been a Principal Investigator for several important projects of the Ministry of Railways, such as compression of railway wagon turnaround analysis research, the development trends and planning research on railway Internet of Things, and so on. He successfully developed the railway hair train safety prewarning auxiliary system.

Mr. Wang received the Railway Administration Technology Talent Award and the Outstanding Science and Technology Worker of the Beijing Railway Bureau award.