

Development of the new CBTC system simulation and performance analysis

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Abstract

This paper introduced the new developed CBTC (Communication Based Train Control) system simulation and performance analysis (hereafter called the simulator) in Southwest Jiaotong University from the system architecture, functions, modeling and algorithms. The simulator is a software program to simulate the movement of trains in the system. It applies the same signal rules of a project without any real hardware or software. A directed graph of track layout and the CBTC moving block train control model used in the simulator are introduced. The main purpose of the simulator is to calculate the system headway and trip speed under the current system configuration and block design. Headway is defined as the time interval between the successive trains moving along the same track in the same direction through the same point. Minimum Design Headway is a key parameter in a system. In this paper, the principle of the in-line station headway and the turn-back station headway calculation are described, and the examples of Chengdu line 1 are provided.

Keywords: CBTC, train control, headway, simulation, performance analysis, safety braking model, safety distance, directed graph.

1 Introduction

With the rapid development of urban railway transit, the new moving block technology CBTC has been the trend of the urban railway Automatic Train Control (ATC) system. To carry out the system simulation and evaluate the system performance is an important step in the system design stage.

The main purpose of the simulation is to calculate the system headway and trip speed with the current system configuration and block design. Headway is



defined as the time interval between the successive trains moving along the same track in the same direction through the same point. Minimum Design Headway is defined as the shortest headway at which the system is able to operate trains continuously. It is determined by the most restrictive point on the guideway. Minimum Design Headway is a key parameter in a system.

This paper introduced the new CBTC system simulation and performance analysis tool developed in Southwest Jiaotong University from the system architecture, functions, modeling and algorithms. The Simulator is a software program to simulate the movement of trains in the system. It applies the same signal rules of a project without any real hardware and software.

The new Simulator is developed with Visual C++, Matlab and GUNPLOT to provide a friendly graphical user interface and easily to configure the operation scenarios. It is not only used for the performance analysis and block design optimization, but also to provide an open platform for the studying of the key algorithms in CBTC system.

2 Software structure and system function

Fig. 1 illustrates the system function and the software structure in the most abstract level.

There are three core modules in the System Simulation and Performance Analysis: ModelLib, Simulation and Analysis.

ModelLib is the train control model library in the software. It includes the following main models called by the Simulation module in every simulation step: Safety Distance model, Braking model, Accelerating model, Station Stop model, Station Departure model, etc. Train control model library is configured offline to be suitable with the particular project using Matlab.

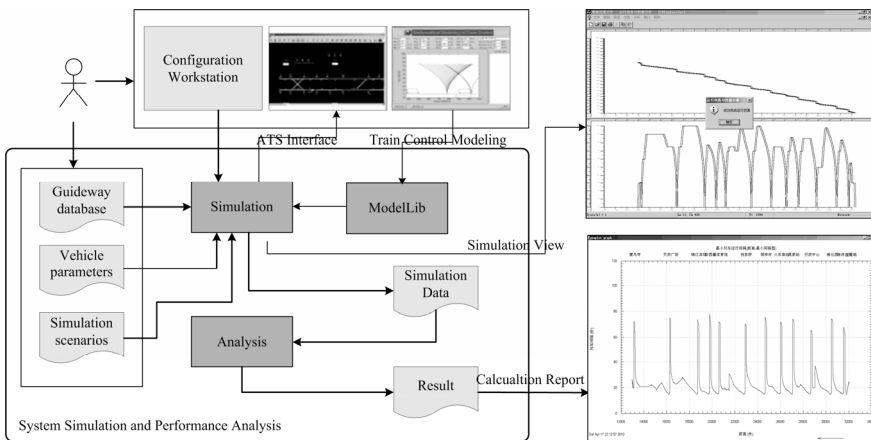


Figure 1: System function and the software structure.

Simulation module simulates the movement of all the trains in the system. The simulation scenarios can be configured in the database or dynamically input from the Configuration Workstation. Input information for the Simulation is Guideway database, Vehicle parameters and Simulation scenarios. The Simulation module has an interface to ATS (Automatic Train Supervision) or ATS simulator to display the real-time system status, such as the wayside status, route status, train type, train location, etc. Another type of simulation view is provided by the graphic Time/Distance and Velocity/Distance plots.

The analysis module imports the Simulation Data recorded by the Simulation module (including: position, velocity, acceleration, grade, speed restriction, target speed, distance to go, etc) and perform the system parameter calculation. Headway/Distance plot is the most important output of the analysis report, from which we can find out the Minimum Design Headway and where the most restrictive point is in the system.

3 System principle

3.1 Guideway database

The guideway database is based on the directed graph, a standard mathematical topology representation. It has a set of Nodes and Edges. Any location where the track diverges, converges, changes the direction of travel or ends is called a Node. The track that connects two nodes together is called an Edge. Typically, the switch and the track end are represented by the node in the topology. Each Edge has a default direction that travels from a source node to a destination node. Normally, the edge direction is same with the track direction. Each Edge and Node has a uniquely ID in the system. The position of the trains and the wayside objects in the system can be defined as $\langle \text{edge}, \text{offset} \rangle$ vector.

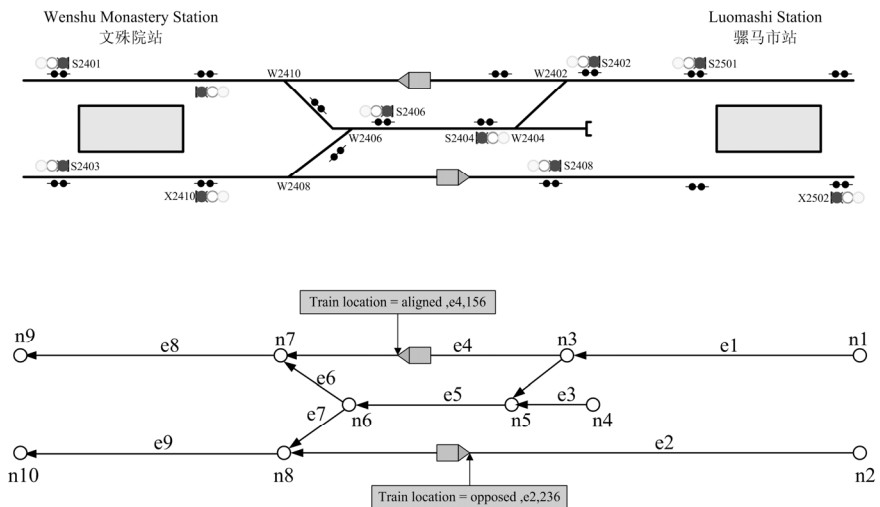


Figure 2: Train location in the directed graph.

Fig. 2 is the example of Directed Graph in Chengdu line from Wenshu Monastery Station to Luomashi Station. Position of train 1 and train 2 is $\langle +e4, 156 \rangle$ and $\langle -e2, 236 \rangle$ respectively.

To have a standard and open mathematical topology representing the guideway database is an important technology for the interoperability of CBTC system. When a train transfers from one CBTC system to another, it downloads the new guideway database at the entrance and report the position to the new Zone Controller. Zone Controller will then calculate the movement authority and send back to Onboard Controller. Both of these messages use the $\langle \text{edge}, \text{offset} \rangle$ method to define the position in the moving block system database.

3.2 System simulation

3.2.1 Safety braking model

Fig. 3 is a typical safe braking model recommended by IEEE 1474.1 [1]. In the figure, the emergency brake curve is the worst-case, open-loop, speed/distance curve a train will follow once the ATP has initiated an emergency brake application. This emergency brake curve must always be less than or equal to the safe speed curve, where safe speed is defined as the speed above which a critical hazard (derailment or collision) could occur.

In this model, safety factors are accounted for in the emergency brake curve, train position uncertainties, and other additional measurement tolerances incorporated in the CBTC system design, and there is no requirement to add additional safety margins.

The ATP overspeed detection curve is the speed-distance curve that the ATP subsystem uses to immediately initiate an emergency brake application, if the ATP subsystem detects that the measured speed exceeds this curve at the measured train location. When the ATP subsystem has initiated an emergency brake application, the ATP subsystem is no longer in the control loop, and the

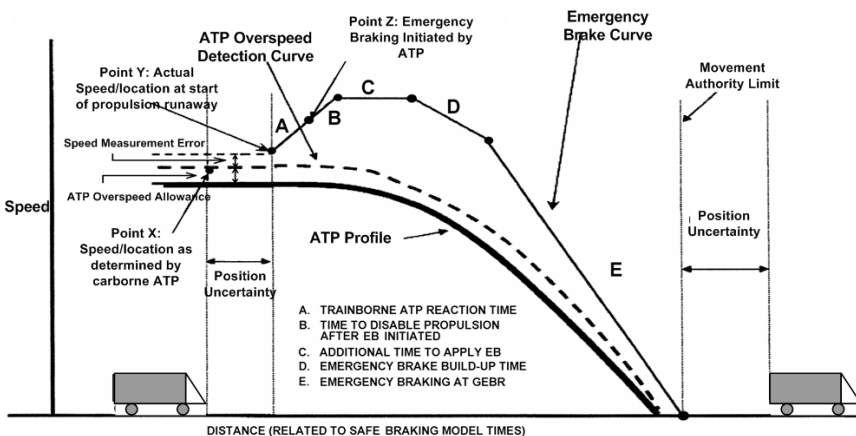


Figure 3: Typical safe braking model.

train will emergency brake at or below the emergency brake curve. The emergency brake curve includes an initial propulsion runaway period, until propulsion is disabled.

The ATP profile curve is the speed-distance curve that is an ATP over speed allowance below the ATP over speed detection curve. The ATP profile is the base curve used by the ATP subsystem.

3.2.2 Safe train separation

Fig. 4 is the Safe Braking Model used in the Simulator. The model defines the principle, assumptions, process and parameters of Safety Distance calculation. All these parameters are imported from the configurable database and can be adjusted to meet the particular project requirements.

This Safe Braking Model is an application of the typical safe braking model recommended by IEEE 1474.1 to calculate the Braking Distance, Safe Braking Distance and the Safety Distance. Braking Distance is the distance to the normal stop point with the normal brake rate. Safety Braking Distance is the braking distance in the worst case. The relationship is,

$$\text{SafetyBrakeDist} = \text{BrakeDist} + \text{SafetyDist} \quad (1)$$

$$\text{SafetyTrainSeparation} = \text{SafetyBrakeDist} + \text{PositionUncertain} \quad (2)$$

In the simulator, ATO curve is N seconds (it is configurable) afterward the ATP enforcement curve. System will always try to drive the train along with the ATO profile in the simulation.

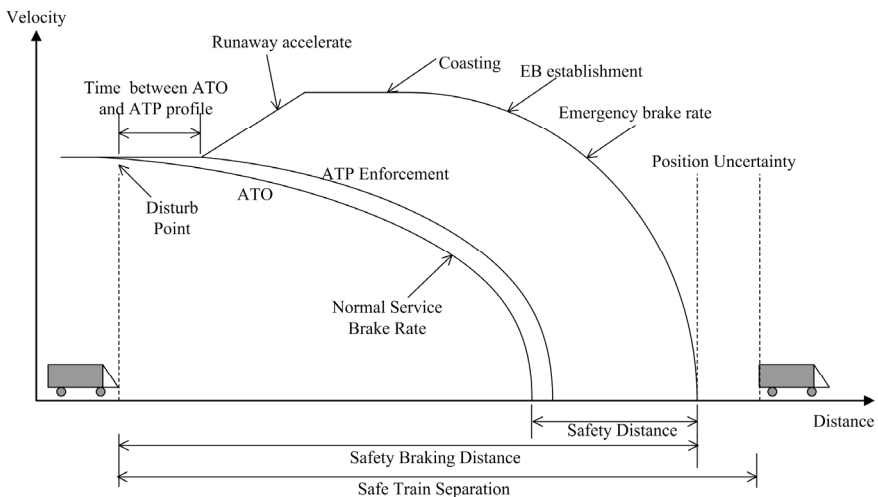


Figure 4: Safe braking model and the train separation in the simulation.

Since the headway is defined as the non-interfering train separation, the Disturb Point is the position of ATO starts to reduce the speed according to braking model. As expressed in eqn (2), Safety Train Separation is the Safety Braking Distance plus the additional Position Uncertainty.

3.2.3 Train movement and train speed calculation

System uses a continuous time slice approach to calculate the train position and velocity. Each time the simulator advances one time slice and calls the train control model to calculate the position information for all trains.

The below functions describes the relationship between time, velocity, and acceleration,

$$\begin{aligned} v_{i+1} &= v_i + a_i \Delta t; \\ \Delta S_i &= v_i \Delta t + \frac{a_i \Delta t^2}{2}; \\ S_{i+1} &= S_i + \Delta S_i. \end{aligned} \quad (3)$$

where

Δt , is the time slice;

v_i , is the train initial speed at the time slice;

v_{i+1} , is the new train speed in this step, also the initial speed for next time slice;

a_i , is the acceleration for this time slice, to simplify the calculation, the constant acceleration is used for one time slice;

ΔS_i , is the distance train travelled in the time slice;

S_i , is the initial position of the train;

S_{i+1} , is the new position of the train.

Every step when the current train velocity is calculated, Simulator will compare it to the ATO profile to determine the drive mode: braking, accelerate, or coasting.

3.3 Minimum headway calculation

As defined before, Headway is defined as the time interval between the successive trains moving along the same track in the same direction through the same point. Minimum Design Headway is defined as the shortest headway at which the CBTC system is able to operate trains at its maximum ATO speed continuously. It is determined by the most restrictive point on the guideway.

3.3.1 Minimum interstation headway

Interstation headway is the time interval of the successive trains without considering the station stop. Fig. 5 illustrates the principle of the minimum interstation headway calculation. In this figure, ATP profile is not showed.

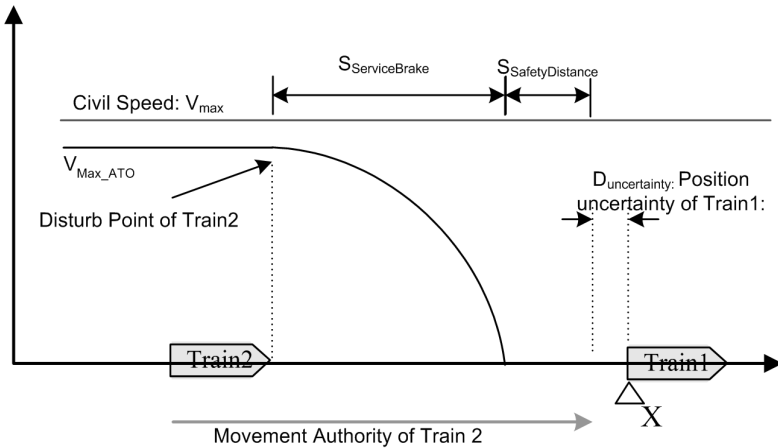


Figure 5: Minimum interstation headway.

The disturb point of train 2 is the train at its maximum ATO speed and start to reduce according to the brake model defined in section 3.2.2. The time of train 2 travelling from the disturb point to the position X (rear of train 1) at its maximum ATO speed is the minimum headway of position X.

Then we can have,

$$T_{Headway} = \frac{S_{ServiceBrake} + S_{SafetyDistance} + S_{TrainLength} + D_{Uncertainty}}{V_{Max_ATO}} \quad (4)$$

where

$T_{Headway}$, is the minimum headway;

$S_{ServiceBrake}$, is the service brake distance for train 2 at the maximum ATO speed;

$S_{SafetyDistance}$, is the safety distance calculated by the brake model;

$S_{TrainLength}$, is the length of train;

$D_{Uncertainty}$, is the position uncertainty of the proceeding train;

V_{Max_ATO} , is the maximum ATO speed of train 2.

From the above principle, in the simulator, minimum headway of each position can be calculated by simulating only one train. Since the simulated train is always trying to run at the maximum ATO speed, system can scan back to find out the position and the time of the disturb point, and then calculate the actual time it travelled through to get the minimum headway.

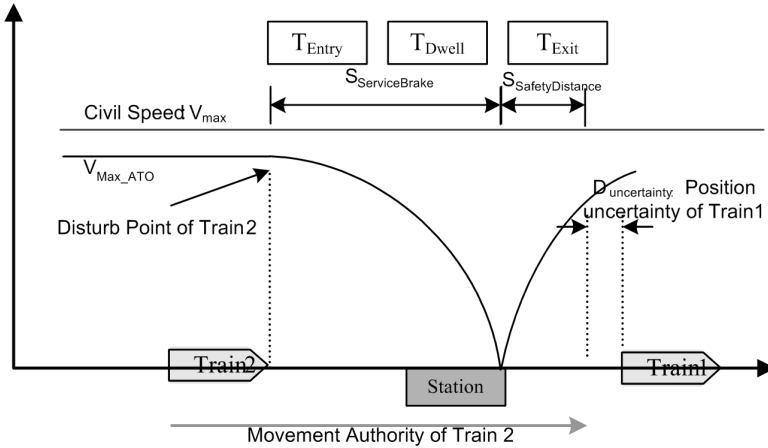


Figure 6: Minimum station headway model.

3.3.2 Minimum station headway

Fig. 6 is the model to determine the minimum intermediate station headway. According to this model, the constraint for the non-interfering train separation requires that Train 1 has cleared the station by a SD beyond the station stopping point (Position uncertainty of the proceeding train is taken into consideration), at the time that Train 2 is a braking distance away from the station stopping point (i.e. the disturb point). System can be configured to use the full service brake rate or a certain constant brake rate to calculate the braking distance.

From this model, we can have

$$T_{Headway} = T_{Entry} + T_{Dwell} + T_{Exit} + T_{Process} \tag{5}$$

where

T_{Entry} , is the time for the train to travel from the disturb point to the station stop point along with the ATO profile;

T_{Dwell} , is the station dwell time;

T_{Exit} , is the time for the train to travel from the station stop point to its rear is an safety distance plus the position uncertainty beyond the station stopping point;

$T_{Process}$, is the system process delay time.

Fig. 7 is the example of minimum interstation and station headway calculation of Chengdu line1 from Luomashi Station to Centaury City Station. Please note that the used guideway parameters and singling system parameters are not exact the same with the real project. If we assume the system is based on moving block principle, we can see the most restrictive point of minimum headway in the system is always at the station area for the reason of station dwell

time. With this figure, we can directly know the minimum design headway and where the most restrictive point is in the system. If the minimum design headway is greater than a project requirement, most likely, it can be optimized at this point.

3.3.3 Minimum turn-back headway

Minimum turnback headway is calculated by multiple trains operation through the switches. The following scenario is the Chengdu line 1 Shexian Lake Station with turnback for 2 trains by the same route.

4 Conclusion

The main purpose of the System Simulation and Performance Analysis tool is to calculate the system headway and trip speed with the current system configuration and block design. It is characterized by scanning all the simulation

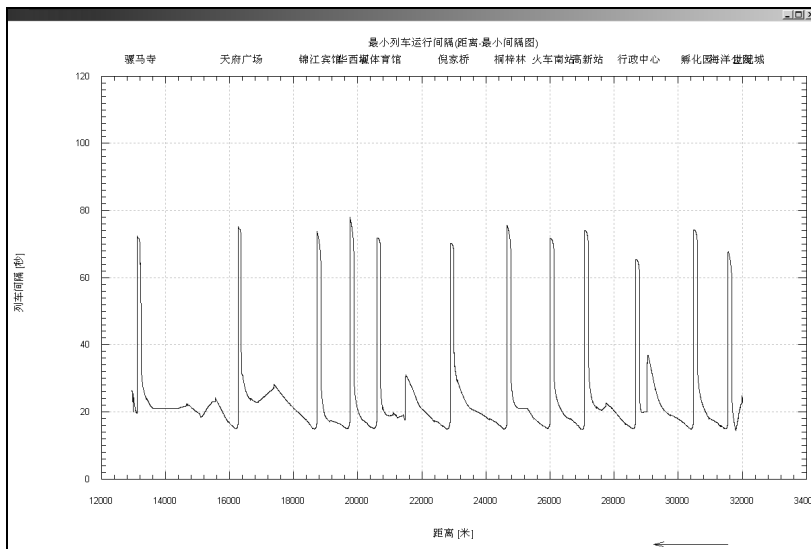


Figure 7: Example of the minimum headway calculation.

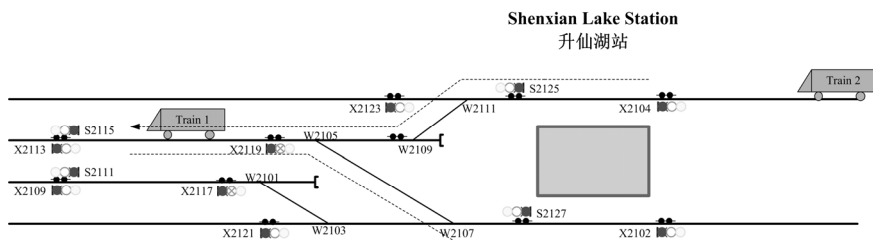


Figure 8: Turnback headway calculation.

Table 1: Turnback headway calculation.

Time	Train 1	Train 2	Action Time
T0	Train 1 departs from Shenxian Lake arrival platform		
T1=T0+N1	Train 1 clear switch W2109 (associated axel counter).		N1 seconds travel time to clear W2109.
T2=T1+N2		ATS commands W2109/W2111 move to normal position	N2 seconds for system processing delay.
T3=T2+N3		W2109/W2111 moved to normal position.	N3 seconds for switch moving.
T4=T3+N4		Movement authority of Train 2 extended to S2125.	N4 seconds for system processing delay
T5=T1+N5	Train 1 Clear switch W2105 (associated axel counter).		N5 seconds travel time to clear W2105.
T6=T5+N6	ATS commands W2105/W2107 move to reverse position		N6 seconds for system process delay
T7=T6+N7	W2105/W21071 moved to reverse position.		N7 seconds for switch moving.
T8=T5+N8	Train 1 arrives the turnback position		N8 seconds travel time
T9=T4+N9		Train 2 arrives at the Shenxian Lake arrival platform	N9 seconds travel time (from the disturbing point)
T10=T8+N10	Train 1 direction changed.		N10 seconds for direction change
T11=max(T7,T10)+N11	Movement authority of Train 1 extended to X2102. Train 1 departs from the turnback position.		N11 seconds for system processing delay
T12=T11+N12	Train 1 Clear switch W2107 (associated axel counter).		N12 seconds travel time to clear W2107.
T13=T12+N13		ATS sets route for Train 2 to the turnback track.	N13 seconds for system processing delay

Table1: Continued.

$T14=T13+N14$		W2109/W2111 moved reverse position, W2105/W2107 to normal position.	N14 seconds for switch moving.
$T15=T14+N15$		Movement authority of Train 2 extended to turnback position.	N15 seconds for system processing delay
$T16= T9+N16$		Train 2 dwell time expired	N16 seconds dwell time
$T17=\max(T15,T16)+N17$		Train 2 departs from Shenxian Lake arrival platform	N17 seconds for system processing delay
Minimum Turnback Headway = T17			

data to calculate the actual distance and time the train travelled, and the train movement is based on train control model library. We used Chengdu line 1 as the example for the design and development validation.

Besides assisting the system design, the tool also provides as an open platform for the train control model optimization study. Some future study is now carried on this platform, such as energy saving, automatic design optimizing of headway, automatic design optimizing of system capacity, etc.

In addition, the tool itself is under the improvement to have faster simulation speed, friendlier user interface, more flexible to build in a new mathematical train control model, easier to create the guideway database, etc.

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