Modeling and Analysis of CTCS-1 On-board Subsystem Based on Simulink / Stateflow

Yangyang He*, Zhongtian Liu

1 Department of traffic information engineering and control, Beijing Jiaotong University, Beijing, 100044, China

2 Department of traffic information engineering and control, Beijing Jiaotong University, Beijing, 100044, China

*Corresponding author’s e-mail: 17120227@bjtu.edu.cn

Abstract. According to the structure of the CTCS-1 train control system and the complexity of its on-board subsystem functions, a model-based method was used to implement the modeling and simulation of the on-board subsystem that using the combination of Simulink and Stateflow in MATLAB software. Then this paper analyses the emergency braking distance and the actual running curve of the train when the following trains at different speeds exceed the emergency braking trigger speed. The results show that the braking distance generated by the established emergency braking trigger model meets the requirements given by train manufacturers, and has a certain safety margin, which also verifies the correctness of the model. The modeling method is intuitive, efficient, visual, and easy understand that the model can well describe the characteristics of the system. The simulation results can provide certain support for the design, research and implementation of the on-board control subsystem of the CTCS-1 train control system.

1. Introduction

As the speed of trains continues to increase, the safety of trains running on existing regular-speed lines (CTCS-0) has attracted increasing attention from all sectors of society. "Research on the key technologies of CTCS-1" is a major project organized by the Railway Corporation. The upgrade of the CTCS-1 optimized the defects and deficiencies of the C0 system, compatible with the many advantages of the C2 and C3, and formed a set of transition train control schemes suitable for new or modified lines below 200km / h. The train control system that uses the target distance continuous speed control mode to monitor the safe operation of the train [1].

CTCS-1 includes on-board equipment and ground equipment. The on-board equipment generates dynamic speed curve according to the movement authority, line parameters, temporary speed limit and other information provided by the ground equipment and vehicle parameters to monitor the safe operation of the train. As an important part of the train control system, the on-board subsystem is not only responsible for real-time safe communication with ground equipment, but also directly to the safe operation of the train in the entire line. The train automatic protection system (ATP) is the core safety control component of the communication based train control (CBTC), and it is also a necessary subsystem in any CBTC configuration method. Its main function is to monitor the operation of the train, to achieve automatic protection of train overspeed, so that the train runs safely at high speed. In order to accurately understand the system requirements, manage the system functions in a standardized
manner, and facilitate the development of the system, it is necessary to model and analyze the functions of ATP of CTCS-1 [2]. At present, Chinese scholars have used a variety of methods to conduct some modeling research on train control system. Most researches mainly focus on the modeling and analysis of CTCS-2 or CTCS-3 using different methods. Relatively little research is done on CTCS-1 on-board subsystem.

This paper uses a model-based approach to model and analyze the system functions of the CTCS-1 on-board subsystem: (1) Arrange the structure and functions of C1 on-board subsystem, thereby establishing a model of system functions. (2) Use Simulink and Stateflow to build a model of on-board subsystem. (3) Procedural simulation validates the feasibility of Simulink / Stateflow model functions. After several modifications, the model is finally verified to be correct. The simulation results can be used to check whether the model is consistent with the expected behavior, and can also lay the foundation for the design of the on-board subsystem [3-4].

2. Function Analysis and Extraction of On-board Subsystem of CTCS-1

Taking the C1 on-board equipment based on wireless communication as an example, the system structure diagram is shown in Figure 1. The on-board equipment adopts a distributed structure. The equipment includes on-board safety computer, balise information transmission module (BTM), STM, speed and distance processing unit, DMI, train interface unit, recording unit, C0 control unit, and the like.

![Figure 1. System structure diagram of CTCS-1 on-board equipment.](image)

Based on the information exchange flow between C1 on-board subsystems and the overall composition of the C1, this article will use Simulink / Stateflow to build an on-board subsystem model. The overall structure of the model is shown in Figure 2. The model mainly includes on-board control subsystem and train model. The on-board control subsystem includes ATP subsystem model and ATO subsystem model. The ATP subsystem model includes model of movement authority boundary, computation model of EBI, and logic model of ATP control. The ATO subsystem model includes model of target speed curve generation and logic model of train control. There is actually no ATO under the CTCS-1. The ATO abstracted in this article is different from the ATO under the CTCS-2 and CTCS-3. It is not a real on-board device. It only extracts functions to provide a simulation environment [5]. Because the structure of the on-board control subsystem is relatively complicated, this article does not model the structure of the on-board control subsystem, but starts with the various functional modules of the vehicle-mounted subsystem to model the on-board subsystem.
3. Modeling of On-board Subsystem Based on Simulink / Stateflow

Simulink is one of the important functional components of MATLAB, which provides an integrated platform for dynamic system modeling, simulation and analysis. Stateflow is a common module in Simulink. Stateflow uses finite state machines to model and simulate discrete event systems, and through combination with Simulink's original modules, it can achieve mixed modeling and simulation with continuous time systems and discrete time systems [6]. The on-board control subsystem model established in this paper includes ATP control logic model, ATO control logic model and train model.

3.1. Model of ATP

The core of overspeed protection is the generation of speed monitoring curves. Generally on-board equipment needs to calculate multiple speed monitoring curves, such as EBI, SBI, etc. The EBI is the basis of other curves, so this article only analyses the calculation of the EBI.

When the on-board subsystem performs speed monitoring according to MRSP, the overspeed protection distance should be considered when entering the speed-limit section, and the rear-end maintenance must be considered when entering the speed-up zone. The trigger speed is

\[ v_{ebi} = v_{perm} + 10 \text{ km/h} \]  

[7]. In the target speed monitoring area, EBI is calculated based on the speed mode curve. Detailed analysis of the discrete state of the on-board subsystem and the continuous behavior of each state during the interval operation of the train. The EBI simulation algorithm flowchart is established as shown in Figure 3. Based on the EBI algorithm flowchart and Stateflow
modeling rules, the EBI stateflow model of the on-board subsystem is established as shown in Figure 4.

The overspeed protection process of on-board subsystem is divided into 3 discrete states: ClosetoLowSpeedArea in front, ClosetoHighSpeedArea in front, and ClosetoEoA in front. The change between the three states depends on the result of the dynamic comparison between the current train position \((v_c, s_c)\) and the corresponding maximum speed limit point \((v_{mrsp}, s_{mrsp})\) and the next speed change point \((v_0, s_0)\). The calculation of EBI in each state is different. When the on-board subsystem is in the state of ClosetoHighSpeedArea, it takes \(v_{ebi} = v_{mrsp} + 10\) to continuously update the EBI before entering the next shift point. When the on-board subsystem is in the state of ClosetoLowSpeedArea, the target speed \(v_t\) is the speed value \(v_0\) of the next speed change point. During the state of ClosetoEoA, the target speed is the speed of the parking point, in this paper the value is zero. In the last two states, the continuous state behavior EBI uses the formula \(v_{ebi} = CalculateMA(v_t, s_{eoa})\) to realize the real-time update of continuous variables. The only difference is that the target speeds \(v_t\) of the two are different. There are many algorithms for EBI, such as the speed step algorithm, time step algorithm, and distance step algorithm. This paper uses the speed step algorithm to calculate EBI based on the braking response time and the system response time.

![Figure 3. Flowchart of simulation algorithm.](image-url)
Divide the entire braking process into several speed intervals $\Delta v(v_1 - v_2)$, assuming that the braking total force of the train remains unchanged in $\Delta v$. The displacement $\Delta s$ of the train within the speed interval is calculated according to the following formula [8].

$$\Delta s = \frac{(v_2^2 - v_1^2)(1 + \gamma)}{2(F_r + 0.41 \cdot (a + b v + c v^2) + (M \cdot g \cdot i) / 1000)}$$  \hspace{1cm} (1)

In formula (1):

$v_1, v_2$ — The final velocity and the initial velocity of the velocity interval (unit: m/s);

$\gamma$ — Train rotation quality factor, the value of YZ25K train model is 1.0582;

$i$ — Gradient of line;

$M$ — Mass of train (unit: T), the value of YZ25K train model is 410t;

$a, b, c$ — Coefficient of experience, the value of YZ25K train model is 5.4, 0.098, 0.00163;

$F_r$ — Braking force (Unit: KN)

$g$ — Braking acceleration, 9.8N/kg.

Add the braking distance $\Delta s$ at all speed intervals during the braking process to get the actual braking distance of the train:

$$S_c = \sum_{i=1}^{n} \Delta s_i$$ \hspace{1cm} (2)

Considering the idling stopping distance $S_k$, the braking distance is $S = S_k + S_c$. When the braking distance reaches the train's travelable distance or the iteration speed is equal to the most limited speed, stop iteration and output the final speed of the last speed interval. This value is the emergency braking trigger speed of the current position. The actual position of the train is calculated periodically. The emergency braking trigger speed can form the EBI. The EBI simulink model of the on-board subsystem is established as shown in Figure 5.
3.2. Model of ATO
The ATO tracks the target driving curve by outputting traction and braking actions to complete automatic driving. The ATO control process is a closed-loop feedback control process. Its control principle is shown in Figure 6. The state of the ATO can be divided into 4 states: traction acceleration (Acceleration), common braking (ServiceBraking), coasting (Coasting) and precise stop (PreciseTrainStopping). This article assumes that the traction force of the following train is the maximum in the Acceleration state; the maximum common braking is applied to the following train in the ServiceBraking state; the acceleration of the following train is zero in the cruise state; the deceleration of the following train in the PreciseTrainStopping state is kept constant to ensure the accuracy of precise stopping. Figure 3 depicts the continuous parts inside the ATO controller, such as the target speed curve. Figure 4 uses the Stateflow model to describe the internal state of the ATO and the transition relationship between those states.

Figure 5. Simulink model of EBI.

Figure 6. Principle diagram of ATO.
3.3. Model of Train
As a controlled object, the accuracy of the model of the train will affect the simulation results. The C1 train group needs to be accurately modeled for dynamics. In this paper, a single-mass train model is used [8]. The train simulation model is shown in Figure 6, which is mainly composed of traction braking calculation and power modules.

4. Simulation and Analysis
The actual line data from Xiangfang North Station to Acheng North Station is used as the underlying data for the model simulation. Model operation simulation is performed in a simulation environment composed of the above models in series. Due to space reasons, the overall composition of the simulation environment is not described in detail.

4.1. Simulation and Analysis of EBI
Braking distance is the main performance index that comprehensively reflects the performance of the train braking device and the actual braking effect. The emergency braking distance of the train is obtained by making the conditions of the train overspeed to "hit" the EBI in the simulation environment.

Figure 9 describes the emergency braking process of a train after triggering emergency braking. In the figure, point A (6807, 54.24) is the starting point of emergency braking, and point B (8124, 0) is
the end point of the emergency braking. The braking distance generated by the emergency braking model at a speed of 195 km/h is 1317 m. Compared with the braking distance standard (less than 1400 m) given by the train manufacturer, the braking distance deviation is within 6% [9], which can explain this article Accuracy of the established emergency braking trigger distance curve model.

Figure 9. EBI of train.

4.2. Simulation and Analysis of Actual Operation Curve
In the control logic of ATO, the important parameter that causes the state transition is the difference $\Delta v$ between the actual speed of the train and the target speed. When the value of $\Delta v$ reaches the threshold of each state, it will cause the transition between the states, thereby performing the actions in each state to control the operation of the train. By setting thresholds for different states, other simulation parameters remain unchanged, and the tracking of the mode curve when the train is running in the area is simulated. The simulation results are shown in the figure 10.

The actual running curve of the train can be seen in Figure 10. This is because the ATO logic control logic is simple, and the control accuracy of the train in each state is low, but the simulation results have reached the expected goal, as can be seen from the figure. The ATO control logic performs state transfer under different external conditions and controls the train's operation well. The train followers allow the curve to run.

Figure 10. Actual running curve of control of the train in ATO.
5. Conclusion
Based on Simulink and Stateflow, on-board subsystem model of CTCS-1 is established in this paper, and the real data is used as the underlying data driver of the simulation model, which increases the usability of the simulation model. The simulation simulates the emergency braking distance generated by the train after the train “hits” the EBI generated by the ATP under different initial speed data. The simulation results show that the emergency braking distance generated by the model in this paper is within a reasonable deviation range, verifying the correctness of the emergency braking model in this paper. In addition, the modeling method in this paper is simple and efficient, suitable for the characteristics of system hierarchy, structure, and randomness. It can clearly simulate the structure and workflow of on-board subsystems. The results of simulation analysis are of great value for the simulation design and application of train control systems.

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