Formal Description and Verification of Mixed Right of Way Scenario for Guided Transport System Based on Vehicle-to-vehicle Communication

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Abstract. GTS (Guided Transport System) is an innovative new mode of urban transportation, which integrates the characteristics of rail transit into urban public transportation. It is a transportation system that meets the needs of low-cost and high-speed construction. According to the actual requirements of GTS, this paper proposes a GTS train control system based on vehicle-to-vehicle communication, and studies its mixed right of way scenario. Using UPPAAL to establish the formalized model of its typical operation scenario and verify the GTS train control system based on vehicle-to-vehicle communication whether it meets the requirements of functionality, performance and security.

1. Background Introduction
CRC Zhuzhou Institute invented GTS as a Bus Rapid Transit operating in virtual rail to improve transport capacity. GTS needs to take safety, path tracking, instant communication and running with society vehicles as tasks. It has the advantages of large passenger capacity, fast speed, punctuality, energy conservation, safety and comfort, etc. It is helpful to solve current traffic congestion in China and build a diversified, three-dimensional and modern urban public transport system.

The current train control system has limitations and cannot be fully applied to the Guided Transport System. Most of the GTS trains that have been put into use adopt the traditional ‘vehicle-ground’ communication mode. Two trains cannot directly complete the information exchange, they have to receive and execute the instructions from the rail side, station and central equipment. After GTS carrying unmanned function, there are many disadvantages for using ‘vehicle-ground’ communication system, as multiple configuration equipment, complex system interface, and heavy dependence on station and rail side equipment, thus leads to the long construction period, multifarious debugging, and high cost of construction and maintenance, which not completely conform to the GTS operations scenario.

Train control system based on vehicle-to-vehicle communication has obvious advantages in the application of GTS. The train communication adopts the "vehicle-to-vehicle" architecture, which makes the vehicle significantly improve its safety, intelligence and efficiency. For example, it can shorten the departure interval, improve the operation efficiency, reduce the configuration of rail-side
equipment, improve the integration degree of various systems, and save the construction and operation cost, which is the development direction of the next generation train control system [1]. Vehicle-to-vehicle communication system transfers the existing ground function to vehicle-mounted equipment. The vehicle-mounted equipment receives the position of the front vehicle through autonomous communication between vehicles, actively detects the obstacles, and autonomously orders line resources from the ground, realizing the concept of "vehicle-mounted equipment as the core".

Therefore, according to the typical operation scenario of GTS, this paper adopts UPPAAL time automaton tool to carry out formal modelling on it, and verifies the requirements of GTS vehicle-vehicle communication system in the functionality, performance and security of this scenario.

2. Formal methods

The formalization method can accurately describe the train control system. It uses mathematical language to describe and verify the system, so as to understand and analyse the system to the maximum extent, and find the potential problems as far as possible. In the field of using formal modelling verification method to verify the train control system to ensure the security, there have been a lot of relevant research results at home and abroad.

Overseas, based on the ERTMS/ETCS specification, a formalized model was proposed by the German railways abroad, and Petri net was used as a unified description method for the whole process of system design [2]. Bacherini used SDL language to describe and simulate the railway signal system [3]. German scholar Jurgen Bohn [4] used statemate tool and dynamic sequence diagram to conduct modelling and design verification of ETCS.

In domestic, Guo danqing used the graphical modelling and simulation tool Simulink to carry out formal simulation and verification of high-speed railway train control system [5]. Wang peng used the modelling method of time automata to formally model and verify each module of the train control system based on vehicle-vehicle communication, which was still in the design stage [6]. Through the use of Simulink/stateflow method, Du Qinghao conducted modelling research on typical scenarios of automatic train operation of CTCS-2+ATO train control system of intercity railway, and verified the system properties [7].

Based on the current research situation at home and abroad, there is still a gap in the research on modelling and verifying the operation scenarios of Guided Transport System with formalized method. At present, there is no special method that can be directly applied to GTS, which greatly restricts the application and popularity of the formalized method in the design, development and verification of the train control system [8-9].

Due to the great difference between GTS and traditional rail trains, the existing train control system of vehicle-ground communication is not suitable for GTS. Therefore, this paper proposes a train control system based on vehicle-to-vehicle communication that meets the actual requirements of GTS. However, this vehicle-to-vehicle communication control system is not yet mature. Therefore, the purpose of this paper is to use a formal method to verify this, conduct a scenario modelling verification study, and verify the results, so as to provide research and development direction for GTS train control system.

This paper adopts the formalized method to model and verify the requirements of the mixed road right scenario of GTS, which can improve the security of GTS in the operation stage and is of great significance to future GTS.

3. Mixed Right of Way Scenario

The right of way refers to the road use right of the traffic participants, which is a kind of right of traffic activities within certain space and time given to the traffic participants by the traffic laws and regulations within the traffic category. It includes the right of driving, right of priority and right of occupation.
The right of way can be divided into the special right of way, the semi-special right of way and the mixed right of way according to the special degree of the right of way. Although the special right of way can guarantee the traffic efficiency of GTS, it costs a lot because it occupies a lot of road resources. Mixed road rights do not specialize in dividing lanes, mixing with other modes of traffic and sharing road resources. Under this form of right of way, the speed of vehicles is low, the safety of intersections is low, and the cost of civil construction is low. In this paper, GTS is suitable for mixed road rights.

When constructing roads, traditional trams often adopt "laying rails in the middle of the road to run trams". GTS train is a rubber wheel vehicle, which can walk directly on the social lane, thus avoiding the process of shovelling out the middle belt and then building the lane. The corresponding result is that the social lane is occupied. After GTS occupies the social lane, it is natural to discuss the rules of mixed right of way. Please see the figure 1.

![Figure 1. Schematic diagram of mixed right of way.](image)

One of the difficulties in modelling the GTS mixed right of way scenario is that the operation of GTS is subject to the urban road rules and social vehicles. On urban roads, it is bound to be interfered and restricted by urban traffic, including the control of traffic lights and paying attention to other social vehicles. Therefore, according to the need of fast operation and the state of road capacity, from the perspective of model simplification, it can be set as GTS exclusive right of way (similar to the BRT), which means that other vehicles are not allowed to enter, so as to achieve fast and safe operation, but this will greatly reduce the road capacity. If efficiency and safety are to be considered, the mixed right of way can be adopted. Other vehicles are allowed to enter and are also controlled by the traffic light at the crossing. The difficulty is to consider the interaction of multiple factors at the same time.

This paper designs a GTS priority traffic light system to coordinate with urban road traffic. This system designs that when the train is about to arrive at the intersection, the established traffic light flow can be changed. When GTS communication system sends a message that it is approaching an intersection, the traffic light controller will change the current light status and operate with a new priority program to ensure that the GTS train can pass safely as soon as possible. Compared with the traditional tram lines, which adopt independent communication signal system, the fast pass of GTS can be realized, and the impact on existing road traffic and pedestrian can be reduced. In addition, due to the coordinated management of traffic lights at road crossings, GTS can not only share the route with social vehicles, but also improve the road traffic capacity and guarantee the operation speed and safety of GTS.

Another difficulty in the GTS mixed right-of-way travel scenario is using the vehicle-to-vehicle communication system to ensure the priority of GTS. The idea is to use the vehicle loaded module to guide the GTS from a few lines on the queue to the same road, GTS vehicle loaded communication module can realize information exchange with other GTS trains on a line and identify each vehicle, provide mobile authorization, so to avoid the same road with multiple GTS trains running which leads to resource waste. Obviously, one safety feature of this communication system is to avoid traffic jams and rear-end collisions caused by the excessive density of GTS trains within a short distance.
4. UPPAAL Modelling for Mixed Right-of-way Scenario

4.1. UPPAAL

UPPAAL was jointly developed by the university of Aalborg (Denmark) and the university of Uppsala (Sweden) in 1995. It is a world-class real-time automatic verification tool. It is used for systems that can be described as the product of nondeterministic parallel processes. Each process is described as a time automaton consisting of a finite control structure, a real data clock and variables. UPPAAL’s simulation detection engine communicates with each other through channels and variables.

UPPAAL has an integrated environment user interface consisting of three main parts:

(1) System Editor: In the editor, the time automata model is referred to as a concurrent series of processes that are instantiated by parameter templates. We set up the model by setting channels and variables.

(2) Simulator: In the simulator, the user can simulate the run and choose to migrate through the process, checking to see if the run is achievable.

(3) Verifier: In the verifier, the user can verify the system properties in the model. The gray represents unverified, green represents passed, and red represents unsatisfied.

4.2. UPPAAL Models

This model comprehensively considers the traffic conditions of vehicles in two directions. Figure 2 is the time automaton model of the traffic light in the other direction. Figure 3 shows the time automaton model of GTS train in its direction. Global synchronization channel (chan) variables are set between two models to ensure the synchronization of state transitions between them. ‘Detected’ indicates that a train has issued a request to go through the intersection, at which time the state of model train is transferred from ‘start’ to ‘waiting’.

Figure 2. UPPAAL model of light. Figure 3. UPPAAL model of train.

Figure 2 is the traffic light model in the other direction. Figure 3 shows the time automaton model ‘train’. In figure 2, there are three main position states: Green, Yellow and Red, which respectively represent the Green, Yellow and Red states of the traffic lights.

The GTS priority traffic light control system designed in this paper meets the following rules: under normal circumstances, the traffic lights are running in the established order, with the green light flashing for 115 seconds, the yellow light for 5 seconds and the red light for 20 seconds (this setting is mainly due to the large traffic flow and the small number of GTS trains). However, when the train is about to pass the traffic light, once the GTS signal is detected, it only needs to wait for 5 seconds to get the 20-second pass time (when the red light in the other direction is on).

In light model, there are several situations. If the current light is green, it will turn yellow immediately. If the current light is yellow, it stays the same. If the current light is red, it will remain the same. The global channel variable ‘ready’ ensures that when the train waits for 5 seconds, the traffic light in the other direction turns Red, so the train starts to pass, and a 20-second pass time is
obtained. The global channel variable ‘finished’ is used to notify the light to change to Green after the train passes through the intersection, thus restoring the previous traffic light control sequence.

Between GTS priority and normal traffic lights control, this system sets up a Bool variable ‘activated’, the variable in train model is set ‘true’ when the state transfers from ‘idle’ to ‘start’, so as to communicate with the traffic light system that it is GTS priority status. While the state transfer from ‘going’ to ‘idle’, ‘activated’ is set false. It means the release of the GTS priority control and the traffic light system goes back to normal. It is this mechanism that enables the traffic light control system to switch between the two states, ensuring the normal operation of urban traffic.

The vehicle-to-vehicle communication model designed in this paper under the mixed right of way travel assumes that there are five GTS trains near the intersection, as shown in Figure 4. Intuitively, when a GTS train (Train1) approaches the intersection, Train1’s vehicle-mounted communication equipment will send a signal to GTS(Train2) in the nearby road. If the road is already running under Train2, Train2’s vehicle-mounted communication equipment will send a steering signal, requiring Train1 to turn to other roads within 10 units of time, so as to prevent multiple GTS trains from entering the same road. Otherwise, if Train1, which is about to enter the intersection, does not receive the signal of turning required by Train2 within 10 units of time, it will start to enter the road within 20 units of time (it needs at least 11 units of time to pass the intersection). All GTS trains about to arrive at the intersection can communicate with each other via the vehicle-to-vehicle communication, and a waiting list will be set up according to their distance to the intersection. When the road is free of GTS again, vehicle-mounted communication equipment on Train1 will send a signal ‘go!’ to let the first GTS train on the waiting list enter the intersection.

5. Verification of Mixed Right of Way Scenario Model
In order to verify whether the control system model is correct, the model grammar checking tool provided by UPPAAL is used for grammar checking at first, and then simulated operation is carried out in UPPAAL's simulator to obtain the message sequence of communication and control between the forward direction of GTS train and the traffic lights in the other direction, as well as between multiple GTS trains. The following statements are verified one by one, which fully shows the correctness and security of the system design and meets the requirements of the system.

Figure 4. UPPAAL model of train1 and train2.
Figure 5. Verification results of mixed right of way model.

Table 1. Verification of mixed right of way model.

| Number | Explanation                                      | Statement                                      | Result |
|--------|--------------------------------------------------|------------------------------------------------|--------|
| 1      | System undead lock                               | A [] not deadlock                              | pass   |
| 2      | GTS can always pass                              | E<>train.going                                 | pass   |
| 3      | A red light can always work                      | E<>light.red                                   | pass   |
| 4      | The red light must be on when the train passes in the other direction | A [] train.going imply light.red                | pass   |
| 5      | Train2 can receive and store messages from incoming Train1 | E<> Train2.Occ                                 | pass   |
| 6      | GTS NO.0 is accessible from the intersection     | E<> Train1(0). Entering                        | pass   |
| 7      | When NO. 0 GTS is entering the intersection, NO. 1 GTS receives the turning signal | E<> Train1(0). Entering and Train1(1).Turn      | pass   |
| 8      | When the NO. 0 GTS is entering the road, other trains at the intersection are in the turning state | E<> Train1(0). Entering and (forall (i : id_t) i != 0 imply Train1(i).Turn) | pass   |
| 9      | At no time will there be more than one GTS in the state of crossing | A [] forall (i : id_t) forall (j : id_t) Train1(i).Entering && Train1(j).Entering imply i == j | pass   |

The results in figure 5 show that the established system can basically meet the requirements described before. According to the explanations in table 1, the designed system can operate at the established green, yellow and red, and can also guarantee the priority of GTS trains under the train communication control system, and meet the system requirements at each time period. A vehicle-to-vehicle communication system consisting of six GTS trains also meets safety requirements.

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