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Research on the autonomous train control system based on vehicle-to-vehicle communication

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Abstract. In recent years, there has been a significant increase in the importance of rail transit, which is largely due to the development of cities. It is anticipated that a new generation of train control systems will be required as the number of passengers increases and track resources become more limited. Seven driving modes of the autonomous train control system based on vehicle-to-vehicle communication are studied in four aspects: system architecture, control method, driving mode conversion, and system safety analysis. By analyzing the correlation between each operating mode in the normal and abnormal operations scenarios, and taking safety into consideration, this paper proposes a train driving mode conversion scheme that covers the whole scenario of train operation by taking safety into consideration in both normal and abnormal operations. This virtual coupling technology further reduces the overall system headway, thereby allowing for more efficient train control systems to be developed, and is intended to provide a useful reference for the engineering of new train control systems.

Keywords: vehicle-to-vehicle communication, autonomous train control system, virtual coupling, driving mode, fail-safe principle.

1. Introduction

Recently, rail transit has taken on a more and more crucial role within the urban transportation architecture, being a key component in the development of urban transportation. The fact that urban passenger flows were distributed unpredictably, both spatially and temporally, meant that rail transit systems were challenged in terms of their capacity and elasticity. Communication-Based Train Control (CBTC) is a widely used train control system in urban transit, whose main technical feature is vehicle-ground-vehicle communication.

In consequence of the rigid vehicle-ground vehicle communication, the original CBTC needs to transmit information to the trackside equipment. The complex structure and the long communication links lead to redundant trackside equipment, high construction costs, and long headways. For the sake of overcoming these drawbacks, a new train control system based on vehicle-to-vehicle communication has been rolled out. This technology was first used by Alstom in the northern French city of Lille [1], reducing trackside equipment by 20%. Dai and Cui proposed to integrate the functions of ZC (Zone Controller) and CI (Computer Interlocking) into VOBC (Vehicle on Board Controller) [2-3], and VOBC calculates the train's movement authority by obtaining the position and speed information of the preceding train. Liu and He have proposed a virtual coupling concept in which the head train manages the platoon and each train follows the preceding train [4-5], reducing the headway and improving the capacity of the line. The driving mode conversion of the CBTC train control system based on vehicle-to-vehicle communication in mainline situations has been analyzed by Zheng [6]. The existing research on train operation mode conversion does not cover the whole scenario, and the impact of the virtual coupling on the train control system has not been studied in depth.

Here, we provide an analysis of the driving mode of the train control system by using the vehicle-to-vehicle communication technology in various situations. Additionally, we analyze the scheme of mode conversion covering the whole scenario of the train operation. As well as that, in order to ensure the reliability of the system under various circumstances in the virtual coupling mode, a safety analysis has been conducted.

2. Autonomous train control system based on vehicle-to-vehicle communication

2.1. System architecture

The autonomous train control system based on vehicle-to-vehicle (V2V) communication is divided into two parts: on-board equipment and trackside equipment, as shown in Figure 1.

The on-board part consists of V2VOBC (vehicle-to-vehicle on-board controller), TCMS (Train Control and Monitoring System), and on-board DCS (Data Communications System) systems. The V2VOBC has the safety protection functions of ATO (automatic train operation), ATP (automatic train protection), ZC, and CI systems required by the traditional CBTC system.

The DCS, ATS (Automatic Train Supervision), and OC (Object Controller) are located on the trackside. ATS is mainly responsible for sending the dispatch schedule to the trains and arranging a safe approach for trains in case of breakdowns. OC controls trackside equipment such as switches and screen doors.

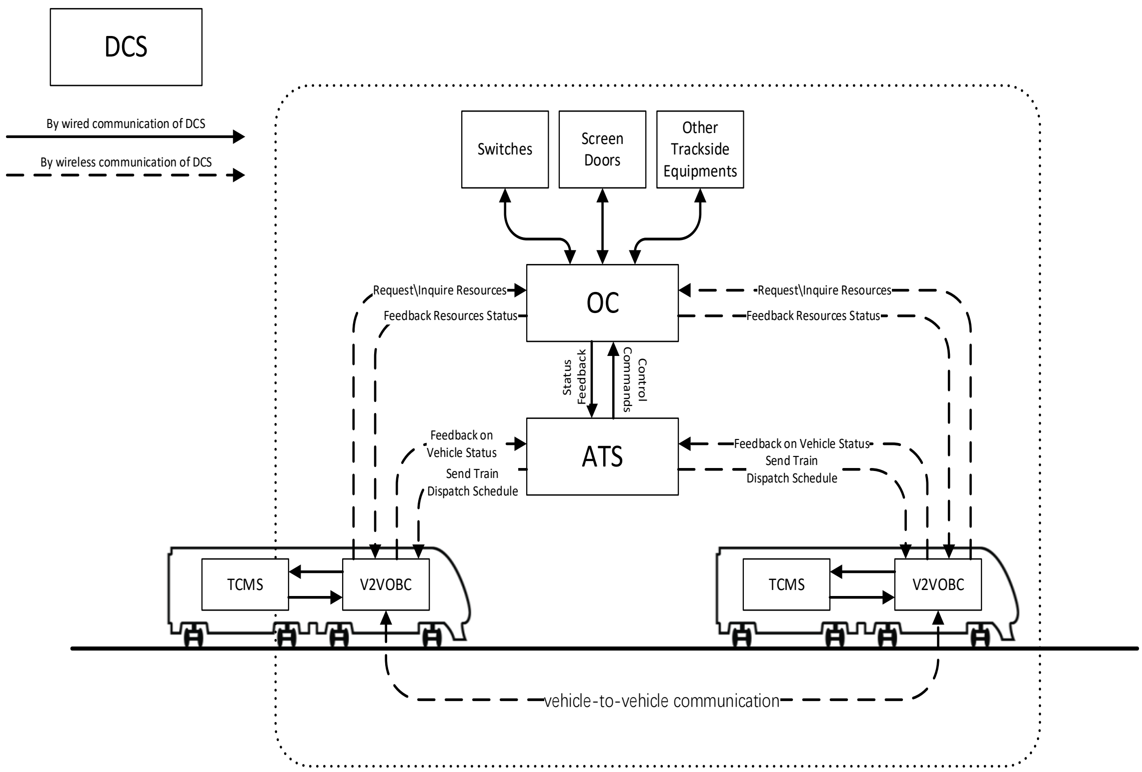

Figure 1. Autonomous train control system based on V2V communication architecture.

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2.2. Control theory

The control logic of the autonomous train control system based on V2V communication is train-centric, which breaks the traditional ground-centric control mode of CBTC. On the main line, the autonomous train control system operates in FAM (fully automatic mode) or VC (virtual coupling) mode.

In FAM mode, ATS sends the dispatch schedule directly to V2VOBC through the DCS system, and V2VOBC verifies the required travel resources based on the dispatch schedule and on-board electronic map. After the preceding train releases the occupied resources, the subsequent train can obtain the released resources from OC in real time.

In virtual coupling mode, the trains in the platoon could be coupled or decoupled according to operational demands. The V2VOBC of the following train obtains the speed and acceleration/deceleration information of the head train directly through V2Vcommunication and matches the speed and acceleration/deceleration with the head train. The platoon operates at a much shorter headway than in normal FAM mode. At the same time, the V2VOBC of the following train maintains the MA calculation based on position to ensure safety in the event of a platoon communication failure. The main features of the autonomous train control system based on V2V communication and the conventional CBTC train control system are compared in Table 1.

Table 1. Comparison of the autonomous train control system based on vehicle-to-vehicle communication and the conventional CBTC train control system.

	autonomous train control system based on vehicle-to-vehicle communication	conventional CBTC train control system
Function	Virtual Coupling Autonomous Protection	Moving Block Interlocking Protection
Mode	FAM、VC、CAM RAM、RMM、STB、SLP	AM、PM、RAM
Equipment	V2VVOBC、TCMS、DCS ATS、OC	VOBC、TCMS、Transponder DCS、CI、ZC、ATS
Interface	ATS-V2VOBC、ATS-OC V2VOBC-TCMS、V2VOBC-OC V2VOBC-V2VOBC、OC-Trackside Equipment	ATS-VOBC、ATS-CI、ATS-ZC CI-ZC、VOBC-TCMS Transponder-VOBC、CI- Trackside Equipment
Design Concept	Train Centric	Ground Centric

3. Driving modes of the autonomous train control system based on vehicle-to-vehicle communication

With the aim of improving the efficiency of the system and ensuring the safety and stability of the operation, various driving modes of the autonomous train control system based on V2V communication have been designed.

3.1. FAM

FAM mode is a fully automatic train operation mode, and the train will automatically upgrade to this mode when conditions are satisfied. In this mode, the train obtains the dispatch schedule and trackside equipment occupancy status issued by ATS and obtains the status of the preceding train through the DCS system. The V2VOBC will autonomously request the occupancy resources from OC and calculate MA in terms of the dispatch schedule issued by ATS. In this model, no manual intervention is required in all operational scenarios.

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3.2. VC

VC mode is a special operation mode based on FAM in which two trains form a platoon and use V2V communication to make it operate fully automatically at very small intervals. Static coupling and decoupling are carried out on the station platform, and the head train operates according to the dispatch schedule issued by ATS. The following train tracks it to form a platoon. In this case, the head train does not need to confirm the status of the following train. Dynamic coupling and decoupling are carried out on the shared route. When the ATS sends coupling demands to the trains, the head train enters the shared route and initiates the virtual coupling, and it calculates MA based on its own position. The following train enters the shared route, obtains the position, speed, and acceleration information of the head train through the V2V communication, and calculates MA by relative speed. When the following train matches its speed and acceleration with the head train and is in a suitable position, it requests virtual coupling with the head train. The head train obtains and verifies the following train's position, speed, and acceleration information. If the status of the following train is within the allowed range of the virtual coupling, the head train agrees to couple. The following train will copy the acceleration and deceleration information of the head train instead of outputting its own MA in light of the relative position. In the event that the platoon's clearance is less than the minimum safety distance, the following train will automatically break to ensure safety. When V2VOBC gets the decoupling command from the dispatch schedule, it controls the train to increase the headway autonomously. When the head train leaves the shared route, the following train keeps an absolute emergency braking distance from it and enters FAM mode after decoupling.

3.3. CAM (crawling automatic mode)

CAM mode is an emergency mode when a train is operating in VC or FAM mode on the main line and encounters a failure in the V2VOBC or TCMS communication networks. The V2VOBC sends a switching inquiry to ATS to change mode to CAM. After being authorized by ATS, the train switches to CAM mode. The train runs to the next station at the maximum speed of 25km/h scheduled by ATS. When the train arrives at the station, the V2VOBC opens the doors and waits for manual disposal.

3.4. RAM (restricted automatic mode)

RAM mode is the emergency mode when a train ATO fault happens in VC or FAM mode on the main line. The V2VOBC immediately changes to RAM mode and will report its existing mode, status, and failures to ATS. The train in RAM mode will automatically run at a maximum speed of 25km/h under the protection of ATP to the preset stopping point outside the next platform and wait for manual disposal.

3.5. RMM (restricted manual mode)

RMM mode is Restricted Manual Mode, which is used when the ATP communication is abnormal or in non-ATS control areas. The ATP is only responsible for monitoring the train speed not to exceed 25km/h and taking emergency brake if the speed is exceeded.

3.6. STB\SLP (standby\sleep)

STB mode is standby mode; the train automatically enters this mode after powering up and completing the self-test, and the vehicle outputs brakes unconditionally. SLP mode is the sleep mode that is triggered remotely by ATS. In this mode, V2VOBC controls the train to power down and transmits the train status to the ATS.

4. Driving mode conversion of the autonomous train control system based on vehicle-to-vehicle communication

4.1. Driving mode conversion on the main line

As shown in Figure 2, the mode of train operation on the main line is divided into two categories: FAM and VC mode for normal operation, and CAM, RAM, and RM for degraded operation mode in case of

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failure.

Transfer A (TA): When the train is running in FAM mode on the main line, it will operate according to the dispatch schedule issued by ATS. At this time, the train will self-check its own status to ensure that the on-board system is fault-free and communicates well with ATS before switching to VC mode. After the mode conversion is complete, the train will be operated as the head train or as the following train in the platoon. Under the situation of static coupling, the procedure is completed at the station. In the case of dynamic coupling, the head train enters the shared route first, and the following train tracks the head train to form the platoon.

TB: If a communication failure between V2VOBC and TCMS occurs in FAM mode, emergency braking of the train is immediately applied by V2VOBC, which sends a request to ATS to switch to CAM mode. The emergency brake is released after receiving permission to switch from ATS, and the train proceeds to the nearest station at a speed limit of 25 km/h according to the ATS's scheduled approach and waits for disposal.

TC: When a train encounters an ATO failure in FAM mode, the V2VOBC immediately reports the failure to the ATS and switches to RAM mode on its own. The V2VOBC sends a drive command directly to TCMS and automatically travels to the RAM preset stopping point outside the next platform at a speed not exceeding 25km/h under the protection of ATP and stops for disposal.

TD: In case of an ATP system failure while the train is running in FAM mode, V2VOBC immediately performs emergency braking and requests for conversion to RM mode. After ATS authorizes it, the train releases the emergency brake, and the driver takes over driving the train. The driver operates at a speed of no more than 25km/h according to the ATS schedule as indicated by the signal.

TE: When the train is operating in VC mode on the main line, it is decoupled in light of the dispatch schedule issued by the ATS. If static decoupling is carried out, the MA will be calculated by the relative position at the station in accordance with the dispatch schedule and run in FAM mode. In cases of dynamic decoupling, the following train will slow down under the command of the head train, increasing the distance of the headway. The V2VOBC of the following train verifies the distance reaches the authorized range of the MA calculated by relative position before the head train leaves the shared route. The trains will automatically switch to FAM mode after leaving the shared route.

TF: If a communication failure between V2VOBC and TCMS occurs in VC mode, the faulty train first issues an emergency brake command to the platoon, and then V2VOBC reports the train’s faulty status to ATS and requests switching to CAM mode. After the ATS allows the faulty train to switch to CAM mode, the platoon releases the emergency brake and decouples. The faulty train switches to CAM mode and proceeds to the nearest station at a speed limit of 25km/h, according to the route assigned by ATS, and waits for disposal. The non-faulty train receives the new dispatch schedule issued by ATS and operates in FAM mode.

TG: When the train is running in VC mode and an ATO failure occurs, the faulty train first issues a command to the platoon to switch to RAM mode and then reports the fault status to the ATS. The ATS issues adecoupling command to the platoon and sends a new dispatch schedule to the non-faulty train. The non-faulty train switches to FAM mode after receiving the new dispatch schedule. The V2VOBC of the faulty train sends a drive command directly to TCMS. It will automatically run to the RAM preset stop outside the next station at a maximum speed of 25 km/h while protected by ATP and stop for disposal.

TH: If an ATP failure occurs in VC mode, the faulty train issues an emergency braking command to the platoon. Then theV2VOBC of the faulty train requests permission to change to RM mode from ATS. After the ATS allowed the faulty train to switch to RM mode, the platoon released the emergency brake and decoupled. The faulty train operates at a speed of not more than 25km/h, according to the driver, according to the ATS schedule as indicated by the signal. The non-faulty train receives the new dispatch schedule issued by the ATS and operates in FAM mode.

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TI: If other types of faults occur in CAM or RAM mode, the V2VOBC will request emergency braking for the sake of train safety. Then V2VOBC reports the fault status to the ATS and requeststo switch to RM mode. After the ATS allows the train to change to RM mode, the driver takes over and operates the train at a speed of no more than 25km/h in accordance with the signalized approach.

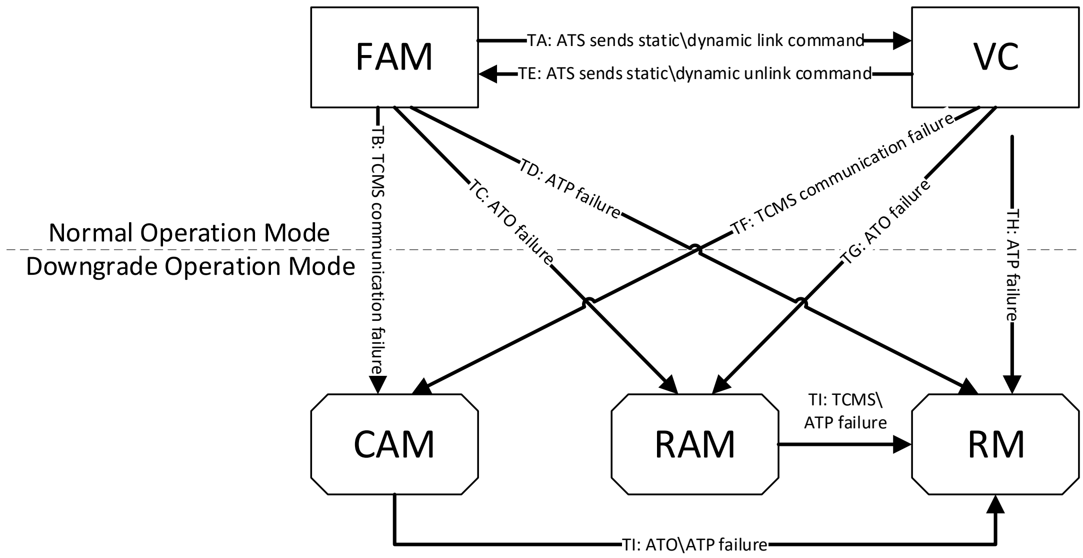

Figure 2. Driving mode changes when the train is running on the main line.

4.2. Driving mode conversion in the depot

As shown in Figure 3, there are two scenarios of trains in the depot, which are the sleep-wake-up scenario and the train-washing scenario.

When the trainin FAM mode enters the depot, the ATS issues a sleeping command. The train requests resources, such as switches to OC, through the DCS system and drives into the depot after confirming the previous train's completion of the entry through V2V communication. The train receives the information with a unique ID from the ground antenna through the sensor and determines whether the train is parked in a specific place based on the signal strength [7]. When the strength of the signal received by the sensor reaches the threshold value, it indicates the train is parked in a specific location. Then, theV2VOBC will send the ground antenna ID to ATS. After confirming the ground antenna ID is the same as the plan, theATS will send the sleep confirmed command to V2VOBC.After receiving the command, the V2VOBC sends a sleep command to TCMS and closes the session with the OC. When the V2VOBC receives feedback from both, it controls the whole train to power down and reports its status to ATS through the nonstop sleep/wakeup" module.

When the ATS sends a wake-up command to the vehicle sleep/wakeup module, the sleep/wakeup module controls TCMS to power up the whole train. The V2VOBC turns to STB mode after the self-test is completed. Then V2VOBC reports the status to ATS and establishes a session with OC, and ATS sends the dispatch schedule to V2VOBC. After finishing all the preparations, the train will change to FAM mode and start normal operation.

When the ATS sends a wash command to the VOBC, the VOBC requests resources from the OC, operates autonomously in FAM mode to the stopping point to be washed, and reports back to the ATS to complete the wash preparation. The V2VOBC controls the train to travel to each pre-set stopping point according to the procedure and reports to the ATS, which then controls the washing machine to perform the corresponding clean operation [8]. When the train is completely out of the washing area, the washing operation is complete, and the VOBC reports the status to the ATS and waits for further commands. The downgrade operation procedure in the depot is identical to that on the main line.

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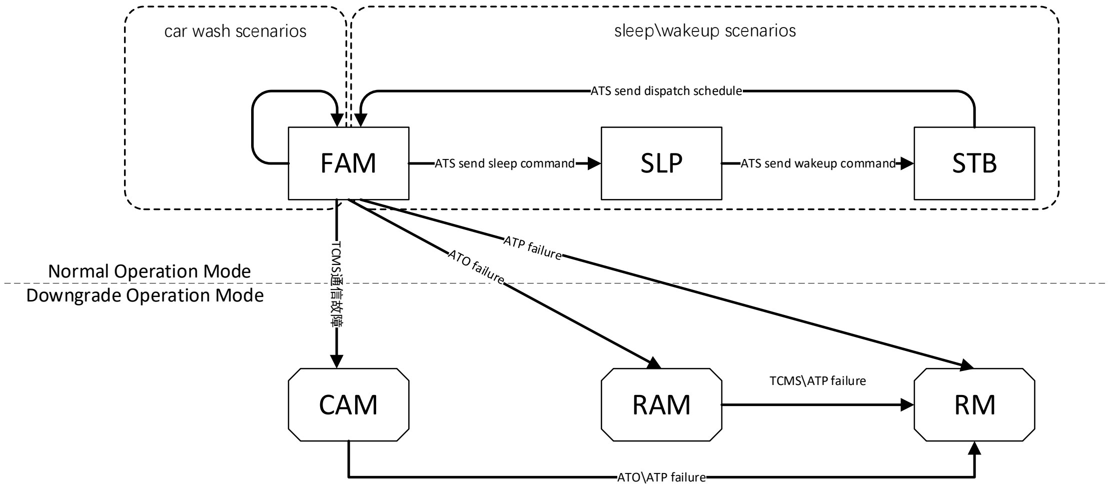

Figure 3. Driving mode changes when the train is operating at the depot.

5. Safety analysis of the autonomous train control system based on vehicle-to-vehicle communication

When the train runs in FAM/VC mode, its on-board V2VOBC will detect the train status in real time and obtain the information of the headtrain and trackside equipment. When the train is in FAM mode, it calculates MA based on its position relative to the next train. By doing so, the train can ensure that evenif the speed of the preceding train is 0, the following train can use common braking to reduce the speed in time. When the train runs in VC mode, the head train uses relative position to calculate MA, and the following train copies the acceleration and deceleration commands from the head train. The following train can generally ensure that the distance between itself and the head train is always greater than the minimum safety distance. V2VOBC can ensure that the train is within the safety envelope at any moment by calculating MA independently.

When a fault occurs in the on-board equipment, V2VOBC will report the type of fault to ATS and analyze the handling method independently. V2VOBC will request from ATS a transfer to the corresponding downgraded operation mode in accordance with the backup plan. Big data analytics algorithms can be used by ATS to calculate a safe approach to the nearest station for the faulty train. The on-board V2VOBC and ATS coordinate to overcome the failure and ensure safety.

6. Conclusion

We propose in this paper a system for running train control based on V2V communication. It provides a comprehensive analysis and explanation of the system from an array of perspectives, which includes system architecture, control mode, mode conversion, and safety analysis, in addition to various aspects regarding system operation. Because the system is train centric, we are able to reduce the number of trackside equipment and our dependence on such equipment. Furthermore, it can also increase the efficiency of the system, improve its safety, and make it easier for operators to maintain it. Using this newly developed system, the train headway, which will result in a further increase in capacity over the original CTBC system.

As an alternative research direction, the research on the development of a train control system that relies on a V2V communication system has yet to come to a consensus standard because it is a more cutting-edge research area. Although each manufacturer or researcher may have their own design concept based on the characteristics of different systems, the autonomous train control system based on V2V communication still adheres to safety principles irrespective of the design concept that each manufacturer or researcher uses. The mode conversions and scenario analyses purposed in this paper provide a reference for upgradations of the existing train control system.

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