Parallel Testing for Centralized Traffic Control Systems of Intelligent Railways

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***Abstract*—The centralized traffic control (CTC) system of intelligent railways plays a vital role in implementing railway dispatching, improving transportation efficiency, and ensuring train safety. However, with the development of high-speed railways (HSRs), the construction of new lines and the upgrading of existing equipment have become increasingly prevalent, posing significant challenges to the safety and reliability of the CTC system. To address these challenges, this article proposes a scenario-driven parallel testing method for the CTC system. We use divisible and combinable scenarios to describe the functionality and processes of testing. Building upon the scenario representation, a virtual-real interactive testing method is adopted, where virtual testing is employed to generate a large number of scenarios simultaneously, thereby accelerating the testing process of the CTC system while ensuring comprehensive testing coverage. Field testing is carried out to validate the reliability of the CTC system in real operational environments, particularly in critical scenarios. The CTC parallel testing system has been deployed in multiple railway bureaus in China, and the deployment results demonstrate that parallel testing can improve testing efficiency, alleviate tester workload, augment the proficiency of on-site construction, and boost the stability and reliability of CTC systems.**

***Index Terms*—Centralized traffic control, high-speed railway systems, intelligent testing, parallel intelligence, artificial intelligence, railway dispatching systems.**

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I. Introduction

THE centralized traffic control (CTC) system of high-speed railways (HSRs) is a complex and comprehensive technology that centrally controls and manages signal equipment in a railway dispatch section [1], [2]. It is a critical component of the HSR transportation command center, ensuring the safe and efficient operation of trains. Through dynamic adjustments and the orderly execution of stage plans, the CTC system provides safe train dispatch services to the transportation production system [3].

With the development of HSRs, the construction of new lines and the upgrade and renovation of existing equipment have gradually increased, posing greater challenges to the safety of HSRs. However, some railway accidents caused by CTC system failures, such as the 2008 Chatsworth train collision in the United States, the 2012 Buenos Aires rail disaster in Argentina, and the 2020 Livraga derailment in Italy, indicate potential safety issues with existing CTC systems. How to ensure the safety of the HSR system and guarantee the integrity and reliability of the CTC system functionality have become pressing issues that need to be addressed in the development of CTC systems [4], [5], [6], [7].

CTC testing is an essential means of verifying system reliability and improving the safety of HSR signal systems, dispatch systems, and personnel. However, the level of intelligence of most existing testing systems is limited. CTC testing systems mainly include simulation testing systems and field testing systems [2]. The simulation testing systems typically build simulation (or semi-real) environments to verify the CTC system through manual confirmation or semi-automated methods, requiring a significant amount of manual labor costs. In contrast, field testing systems attempt to verify the performance of the CTC system under almost all possible conditions in the real world. However, when the complexity of the CTC system is high, the possible conditions can grow exponentially, resulting in high time costs for field testing [8], [9]. Moreover, many external factors, such as geography and weather conditions, are difficult to test flexibly in the real world [1]. Therefore, field testing alone may be inadequate to complete comprehensive system testing within a limited time.

To improve testing efficiency while ensuring comprehensive testing and reliability of the CTC system, we propose a parallel testing method. Parallel testing involves interactive virtual and field testing based on scenario engineering [10], [11], and has already been successfully applied in autonomous vehicle testing, accelerating the assessment and advancement of vehicle intelligence [12], [13], [14]. In parallel testing for CTC systems, all testing processes are built as scenario representations, with scenario pass rates as the evaluation metric, driving the testing system to evaluate the importance of each scenario and generate challenging key scenarios to comprehensively and specifically evaluate the CTC system.

Parallel testing for CTC systems includes four stages. First, we use scenario engineering to describe all testing scenarios as typical independent scenarios, which can be further divided into sub-scenarios and combined into comprehensive testing scenarios. The temporal, spatial, and some typical features of each scenario will be parameterized. Second, based on scenario descriptions, corresponding testing scenarios are generated within parameter space of the scenario using sampling methods in accordance with certain requirements. Third, we apply the generated scenarios through virtual and field testing interactions to facilitate comprehensive testing for the CTC system. Finally, the performance of the CTC system is verified and validated in each scenario, and the importance of each scenario is parameterized based on the evaluation results. The sampling distribution is then reconstructed to generate challenging key scenarios for the CTC system.

In this article, we elaborate on the methodology and application of parallel testing for CTC systems, and the main contributions of the article lie in the following aspects:

1) We propose a new testing method for the CTC system, called parallel testing, which allows for comprehensive and intelligent testing of all modules for the CTC system and improves testing efficiency.
2) Parallel testing helps improve the CTC system's safety, reliability and trustworthiness by combining virtual and field testing. This approach uses virtual testing to drive key scenarios in field testing and conducts multiple virtual testing scenarios simultaneously during field testing.
3) We have deployed the parallel testing system in numerous railway bureaus across various cities in China, such as Beijing, Chengdu, and Zhengzhou. The deployment results indicate that the proposed method greatly decreases the testing cost of the CTC system, reduces the workload of signal personnel, improves the efficiency of construction and transportation and increases the stability and reliability of the system.

The remainder of the article is structured as follows. Section II reviews the history of CTC systems, the testing method of CTC systems and the development of parallel testing for autonomous vehicles. Section III introduces the parallel testing method for the CTC system. Section IV presents a case study of the application of Beijing CTC parallel testing systems. Finally, Section IV concludes the article.

II. Related Work

A. Development of CTC Systems in Railways

The term CTC first emerged in the United States [15]. In 1927, the American Railway Association named this technology for centralized control within sections based on signals and put the corresponding equipment into use in the New York Railroad system. The CTC system in the United States, after long-term development, has become a comprehensive train management and dispatching system [16]. For example, Burlington Northern Santa Fe company principally conducted its operations within the Midwest region of the United States, with about 65% of the routes within its operational range under the unified dispatch of the CTC system. In Asia, Japan's CTC systems developed relatively early [17]. Japan absorbed the experience of the American centralized dispatch and formed a decentralized autonomous CTC paradigm considering the unique characteristics of the country's terrain and railway networks [17].

In China, the construction of automatic railway dispatch command systems began in the 1960s [18]. After half a century of improvement, the Ministry of Railways officially released the feasibility study report on the construction of the dispatch management information system (DMIS), which was later renamed the train dispatching and commanding system (TDCS) in 2005 [19]. The TDCS covers modern railway transportation dispatch command management and control across the entire railway network. After the construction of the Qin-Shen passenger railway line in 2003, the Ministry of Railways formulated the "Technical Specifications for the Decentralized Autonomous CTC System (Provisional)", deciding to construct the decentralized autonomous CTC system to address the contradictions between train adjustment and shunting operations [20].

After the introduction of the decentralized autonomous CTC system in China, the system underwent pilot operation on some routes, generally referred to as the CTC 1.0 system [1]. With the rapid development of railway construction in China, the CTC system gradually expanded its functions to address transportation requirements, evolving into a CTC system that essentially meets the needs of HSR transportation. This CTC system is commonly known as the CTC 2.0 system [21]. Around 2010, the CTC system expanded its interfaces with other signal systems such as the temporary speed restriction server (TSRS) and radio block center (RBC), and increased information integration with other systems like transporting dispatching management systems (TDMS) and power supply dispatching management systems (PDMS). This enhancement has strengthened the connection of CTC systems with transportation information integration platforms, and improved the technical implementation plan. In 2015, China Railway Corporation officially issued a new generation of CTC technical conditions (Q/CR 518-2016), stipulating characteristics of CTC systems, forming the CTC 3.0 system [22].

In last five years, artificial intelligence (AI) technology has found extensive application in CTC systems. Some studies targeted the CTC center and employed intelligence heuristic methods and learning-based approaches such as reinforcement learning to enhance the operational efficiency of the system through dynamic scheduling [23], [24], [25]. Other research focused on train control and utilized intelligent control methods to facilitate efficient operation control and decision-making [23], [26], [27]. Some researchers proposed new control architecture systems, such as the autonomous train control system, which combines data fusion and prediction to further enhance coordination and efficiency in train movements [28]. These AI-integrated HSR scheduling and train control technologies have propelled the development of CTC systems towards safety, reliability, and efficiency.

B. Development of Testing for CTC Systems in Railways

The earliest testing method for CTC systems is manual testing, in which professional testing personnel conduct individual testing on each module of the system at the real site [29]. The methodology was initially implemented in the CTC system in the United States, and in the 1960 s, this testing method was still widely used. Its advantage is that testers can directly observe the conditions of the testing site, facilitating the rapid detection of problems. However, manual testing requires a significant amount of manpower and resources, resulting in high testing costs. Additionally, the testing is influenced by the individual quality of the testers, which means the reliability and accuracy are somewhat limited. Lastly, both the coverage and efficiency of the tests are relatively low [30].

Virtual testing is a semi-manual, semi-automated testing method developed based on computer simulation technology [29], [31]. It uses computer programs to simulate real and dynamic environments, reducing the consumption of manpower and resources and improving testing efficiency [32]. The French railway department personnel utilized the computer simulation to replicate the HSR environments and tested their own CTC systems based on the simulation, thereby demonstrating the effectiveness of employing the track as the central command center. The virtual testing method was also used in Japan to simulate the integrated dispatching system of the Shinkansen, and to validate the effectiveness of decentralized autonomous CTC systems. However, virtual testing has gradually exposed the following issues during the high-speed evolution of CTC systems: 1) involvement of multiple external systems with various deployment environments and stringent usage conditions for different external simulation software [33]; 2) inability to achieve automated testing, with the testing process primarily relying on manual operations; 3) difficulty in simulating various abnormal situations on-site within the simulation environment. Time constraints and interference factors affecting transportation prevent the achievement of full-scenario case coverage testing.

C. Parallel Testing

Parallel testing originated from parallel systems that refers to a collective system composed of a natural real-world system and one or more corresponding virtual or ideal artificial systems [34]. Based on the paradigm of virtual and real interactions, researchers have proposed a series of parallel systems in various domains, such as parallel HSR systems [24], [35], [36], parallel transportation systems [37], [38], [39], [40], [41], [42], and parallel driving systems [43], [44], [45]. These parallel systems provide effective solutions to address complex system issues in their respective domains.

Combining the principles of parallel systems, parallel testing similarly adopts a combination of virtual and real interaction for intelligent testing, and leverages scenarios engineering to build trustworthy intelligent systems [46], [47]. Currently, parallel testing has been successfully applied to intelligent testing of autonomous vehicles, allowing closed-loop evaluation and enhancement of vehicle intelligence [12], [48]. In this approach, field testing is used to validate the level of intelligence of the vehicle in the real environment. Simultaneously, virtual testing leverages techniques such as parallel vision [49], [50], [51] and parallel learning [52], [53], [54] to rapidly generate a large number of diverse virtual scenarios based on real data, thereby testing various functionalities of intelligent vehicles and identifying the most challenging testing tasks. During the testing process, scenario engineering encompasses six dimensions: intelligence and index (I&I), calibration and certification (C&C), and verification and validation (V&V). It facilitates a comprehensive and efficient evaluation of autonomous vehicles, propelling the development of robust and reliable autonomous driving systems [10], [46], [47].

Parallel testing has successfully supported the Intelligent Vehicle Future Challenge of China (IVFC), the world's largest and longest-running autonomous driving competition. Since the inception of IVFC in 2009, the parallel testing system has been continuously upgraded to perform systematic, quantitative, automatic, and safe testing for industrial autonomous vehicles [14].

III. Parallel Testing for CTC Systems

A. Overall Framework of Parallel Testing for CTC Systems

The motivation of parallel testing for CTC systems is to achieve comprehensive and efficient testing of CTC systems in independent scenarios such as interfaces, signaling & communication (S&C), transportation, as well as comprehensive scenarios like schedule-based train routing and temporary speed limit commands, through intelligent testing involving virtual-real interaction. This aims to accelerate system testing efficiency and reduce human resource costs. Meanwhile, parallel testing can also help to improve system performance to ensure the reliability, safety, and operational efficiency of CTC systems.

Parallel testing for CTC systems includes a process that involves both virtual testing and field testing, which are closely integrated. Virtual testing is based on artificial CTC systems built on the real CTC system. The artificial systems are constructed using agent-based methods and are equivalent to the real system, supporting comprehensive and efficient virtual testing. Field testing is used to verify the safety and reliability of the real CTC system. In parallel testing, virtual testing is performed synchronously with field testing, where virtual testing serves as a supplement to field testing by conducting multiple concurrent and diverse testing scenarios. The testing process via virtual-real interaction can improve the thoroughness of the validation as well as the efficacy of the verification process for CTC systems.

The parallel testing method builds a testing process based on scenario engineering and forms a closed-loop process to achieve cyclic iteration and acceleration of testing, ensuring the safety and reliability of the CTC system. As shown in Fig. 1, the parallel testing process for CTC systems consists of four parts: CTC

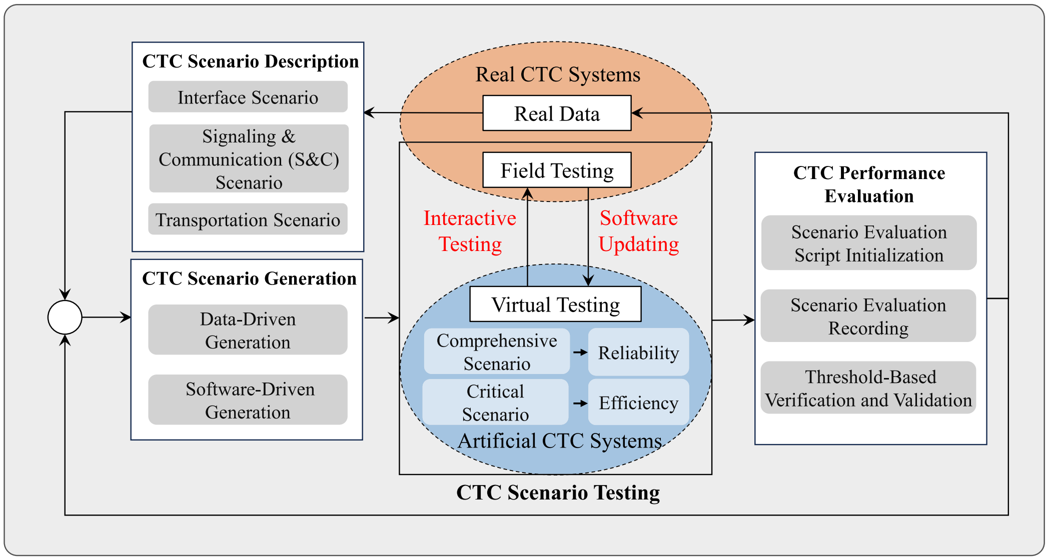

Fig. 1. Overall framework of parallel testing for CTC systems.

scenario description, CTC scenario generation, CTC scenario testing via virtual-real interaction, and CTC performance evaluation.

CTC scenario description decomposes all testing contents and functional elements of CTC systems into temporally and spatially combinable modules, and realizes full scenario characterization through module parameterization. Specifically, we describe the CTC system testing scenario as three modules: interface scenario module, S&C scenario module targeting static elements, and transportation scenario module targeting dynamic elements. Each independent testing scenario can be further broken down for functional testing of various parts of the CTC systems. After completing independent scenario testing, we combine the three types of independent testing scenarios temporally and spatially to form integrated testing scenarios for full-process testing of CTC systems.

CTC scenario generation is based on the parameterized scenario description and is performed through an automated testing design for automatic CTC scenario generation. Depending on the testing object, scenario generation can be divided into data-driven generation and software-driven generation. Data-driven generation uses a learning-based automated testing method to focus on the consistency between the artificial CTC system data and the real CTC system data under various scenarios. Software-driven generation targets scenarios such as software updates, using an experience-enhanced mechanism, and fully traverses all functions of the software to test whether the internal logic of the CTC software meets expectations, thereby quickly verifying its reliability.

CTC scenario testing, based on the generated testing scenarios, realizes comprehensive testing of the CTC system through virtual-real interaction and accelerates the testing process. Scenario testing includes an independent virtual testing phase and a virtual-real interaction phase. Virtual testing generates various independent scenarios and combined scenarios to conduct large-scale comprehensive testing of the various modules and subsystems of the CTC system to test the system's reliability. Also, virtual testing allows us to flexibly generate various challenging scenarios by setting external elements, and thus enhance testing efficiency. In the virtual-real interactive testing phase, virtual testing is performed concurrently with field testing, and the two communicate in real-time. Virtual testing generates more scenario parameters under field testing scenario parameters, conducting more diversified and efficient performance tests of the artificial CTC system, thereby ensuring the overall safety and reliability of the real CTC system and the artificial CTC system.

CTC performance evaluation uses an experience-enhanced automatic discrimination technique, with scenario pass rate as a comprehensive performance evaluation indicator of the CTC system. The evaluation process includes three parts: scenario evaluation script initialization, scenario evaluation recording, and threshold-based verification and validation. First, we initialize the automated testing tool and set the consistency comparison rules of the testing tool according to the experience-enhanced memory library. Then, we load the testing scenario scripts, conduct scenario testing, and record the evaluation results in the testing scenarios. Finally, the consistency between the testing results and the expected results is compared using a threshold method. If the difference between the testing results and the expected results is below the threshold, it is considered to have passed the scenario testing; otherwise, it is considered to have failed the scenario testing.

Through the implementation of a scenario-driven, closed-loop parallel testing paradigm, we have conducted a comprehensive and efficient evaluation of CTC systems, thereby ensuring that their safety and reliability are upheld to the highest standards.

B. *Artificial CTC Systems*

We use the agent-based distributed network structure to build artificial CTC systems, and the artificial system completely

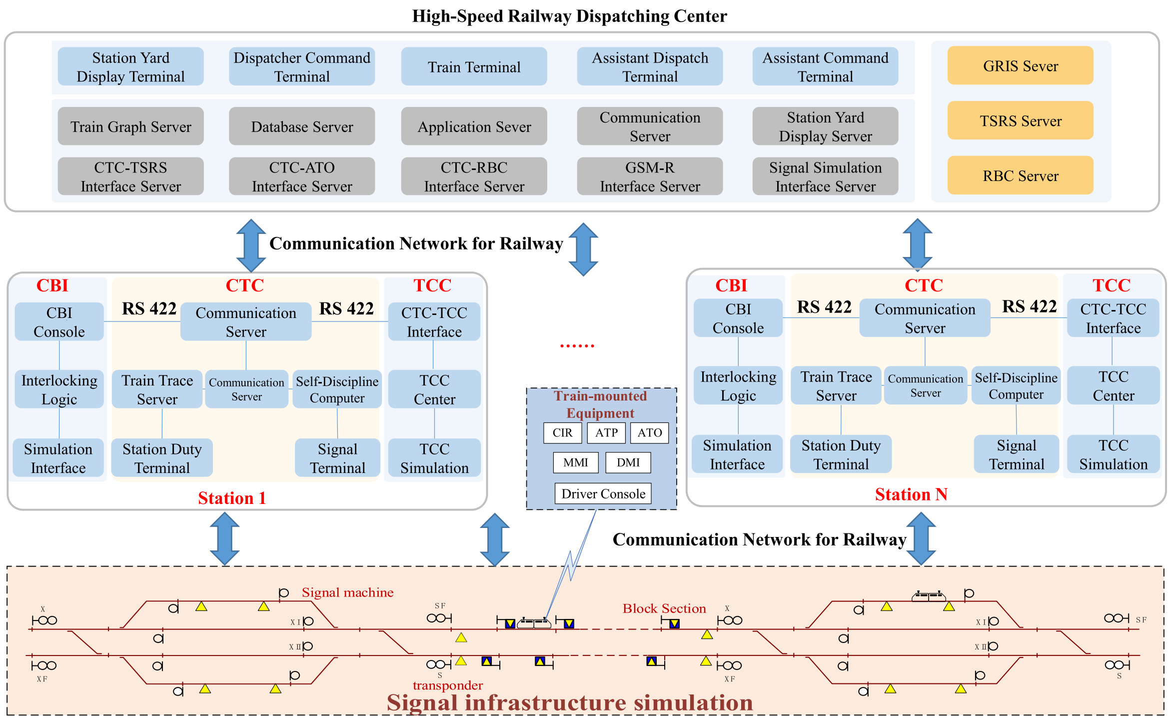

Fig. 2. Overall framework of the artificial CTC systems.

simulates the real CTC system. As shown in Fig. 2, the system mainly consists of four modules: the dispatching center subsystem, station subsystem, communication network subsystem, and signal infrastructure simulation.

The dispatching center subsystem is responsible for preparing and adjusting the train operation plan and sending the plan to the station. Artificial dispatching centers mainly include the following parts:

1) Simulation of complete CTC system functions: The simulation-based system adopts the real CTC system application software and support all operations of the CTC system, mainly including stage plan, dispatching command, regulation and supervision display, station control, temporary speed limit, train tracking, train picking and reporting.
2) Simulation of TSRS: The simulation-based TSRS communicates with the CTC system according to the standard interface protocol. The server supports the whole process of operation simulation such as speed restriction command formulation, sending, checking, setting and canceling, as well as real-time speed restriction status inquiry and yellow light band display.
3) Simulation of RBC: The simulation-based RBC is equipped with a software-defined module to communicate with CTC systems according to the standard interface protocol. In addition, RBC sends the simulated train running status, position, speed and movement authorization information to the CTC system.

The railway station subsystem is responsible for managing and controlling the transportation activities at the station, ensuring safe and smooth operation of the trains. Artificial station subsystems mainly include three parts:

1) Autonomous computers: We adopt virtual simulation technology to simulate the operation of all autonomous computers in the dispatching section. The virtual autonomous computer ensures that its station data, the data in “Station Operation Detailed Rules” (SODR), and function configuration are fully consistent with the production system, and supports all functions such as automatic and manual dispatching.
2) Simulation of interlocking systems: The artificial interlocking system responds to the control commands sent by the autonomous computer, generates changes in the status of the signal equipment according to the interlocking rules, and feeds back to the autonomous computer. The interlocking system realizes the functions of approach selection, signal opening, guiding pickup, button blocking and equipment fault alarm according to the existing approach table and signal logic.
3) Simulation of train control centers (TCCs): The artificial TCC communicates with CTC systems according to standard interface protocols, simulates the generation of interval state and feeds back to CTC systems.

The artificial communication network subsystem is a dual-ring network consisting of communication devices and transmission channels. Communication is mainly realized by the global system for mobile communications-railways (GSM-R) transmission simulation software. The software transmits information such as train number, speed and position according to the standard interface protocol and CTC system communication, and can receive and display information such as wireless dispatching orders and wireless approach forecasts from the CTC system. Moreover, GSM-R can communicate with RBC systems

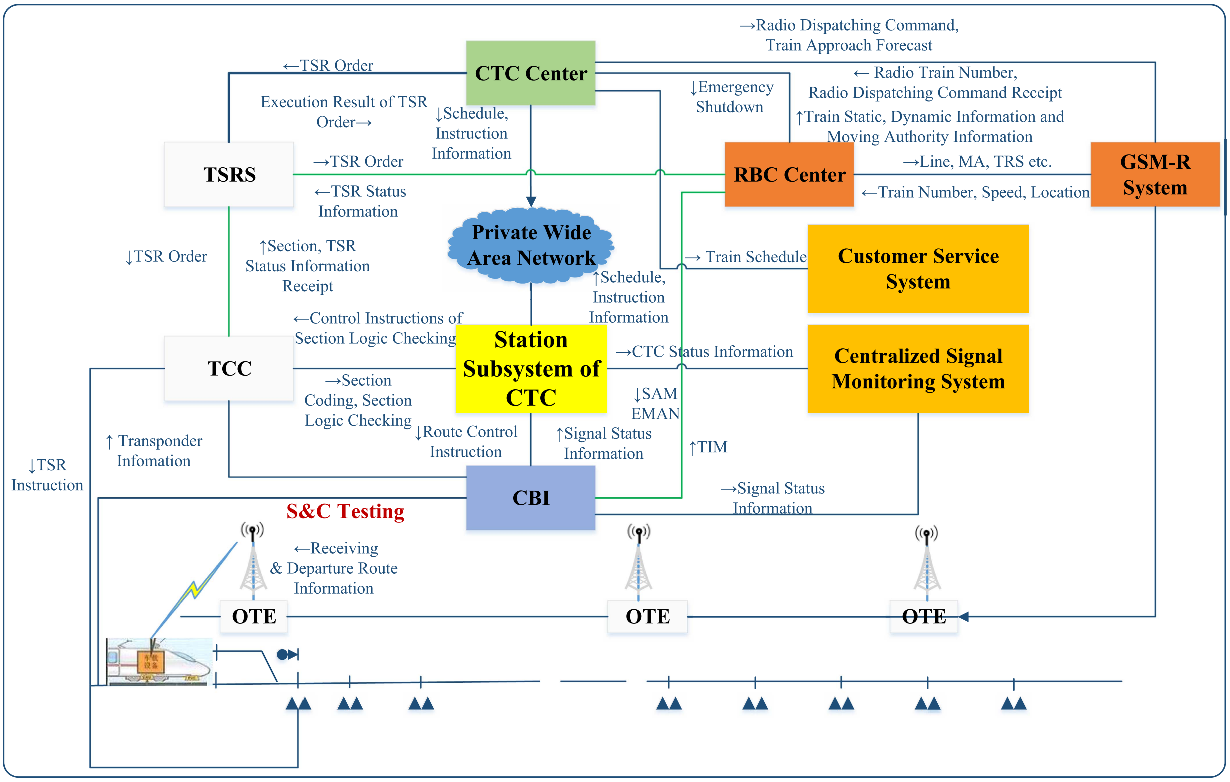

Fig. 3. HSR signal connection diagram.

to transmit information such as line and speed limit of traffic permit.

The signal infrastructure simulation models the dynamic operation of trains in the dispatching section, thus laying the foundation for train operation and the construction of the three subsystems. The simulation environment is constructed based on the real line data of the HSR. Specifically, stations and bridges consistent with the real location are built in the virtual environment and the line topology is drawn. The scenario-based simulation enables the train operation to automatically generate red light band movement information in accordance with the signal rules and trigger related systems such as computer-based interlocking (CBI), TCC, RBC and GSM-R to generate correlation outputs.

C. CTC Scenario Description

The purpose of the scenario description is to deconstruct all the testing content and functional elements of CTC into separable modules, and achieve a comprehensive scenario representation through parameterization and spatiotemporal arrangement of these modules. In this article, the testing scenarios are first described as three independent modules: the interface scenario module, the S&C scenario module focused on static elements, and the transportation scenario module focused on dynamic elements. Each independent testing scenario can be further divided to test CTC's various functional components. After the independent scenario testing is completed, the three independent testing scenarios are combined spatiotemporally to form a comprehensive testing scenario for the entire CTC testing process.

Independent testing scenarios, namely the interface scenario, S&C scenario, and transportation scenario, encompass almost all elements of CTC testing. The testing subjects include real and artificial systems for CTC, railway stations and on-board train equipment, as well as personnel in the CTC center and the station. Fig. 3 shows the signal connection relationships in HSRs that are the focus of all testing scenarios. In this section, we mainly elaborate on the definitions, testing content, classifications, and scenario variables of these three independent testing scenarios, with scenario variables serving as search parameters for generating the integrity scenarios in the next step.

The interface scenario focuses primarily on testing the consistency of interface data between the CTC system and downstream devices from different manufacturers, including CBI and train control system interfaces. The CBI interface is the interface between the CTC and the station interlocking system. This scenario includes display data interfaces, command operation data interfaces, and route data interfaces. The testing content involves adjusting different routes and control operations based on the station interlocking code table from interlocking manufacturers to test the consistency of the three types of data display and command issuance between the CTC system and the interlocking system. The train control system includes TCC, TSRS, and RBC. Interface testing of the CTC and train control system is performed by connecting the CTC (including the central system, dispatching console and station system) to the train control simulation system (including TCC, TSRS and RBC). The testing tries to verify the consistency of the CTC's train operation terminal, signal machine of dispatch console section, block layout, and status with the train control system, as well as the consistency of speed restriction commands issuance and yellow light band display with the train control system.

The S&C scenario testing oriented towards static elements is organized by various S&C departments, in cooperation with dispatching and computer interlocking manufacturers. The purpose of S&C testing is to verify whether the manual control function of the dispatch center is working properly and whether the control function is fully implemented according to the operator's intention. The S&C testing is divided into two parts: the railway terminal S&C testing and the dispatching console S&C testing. The railway terminal S&C testing contains four sub-scenarios: consistency testing of the information displayed by the railway terminal machine and the operating machine; consistency testing of the operating information of the railway terminal machine and the execution information of the computer interlocking machine; testing of the safety measures executed by the decentralized autonomous CTC system according to SODR; and testing of the control mode switching. The dispatching console S&C testing is also divided into four sub-scenarios: consistency testing of the site plan of the dispatching workstation and the display of the computer-based interlocking system operating machine; consistency testing of the operating information and the execution information of the computer interlocking operating machine; safety testing based on SODR; and testing of the route triggering and speed restriction functions.

Transportation scenario testing, focused on dynamic scenarios, is used to verify all CTC functions of the dispatching center. To achieve complete CTC function testing while ensuring system safety, the transportation scenario testing first conducts virtual testing and then conducts field testing based on the stability and reliability of the system. In virtual testing, the artificially constructed CTC system includes simulation of the complete CTC center and railway station (application server, communication server, dispatching console, autonomous computer, and railway terminal), computer-based interlocking system, and outdoor equipment. By simulating various train operation scenarios, the testing content includes all functions of the dispatching center, such as automatic routing, monitoring display, mode switching, as well as data and configuration correctness.

D. CTC Scenario Generation

Automated testing scenario generation based on CTC scenario descriptions is performed via automated testing designs. According to the testing object, scenario generation can be divided into two parts: data-driven testing scenario generation and software-driven testing scenario generation. The three independent testing scenarios described in Subsection III-C, namely interface scenario testing, S&C scenario testing, and transportation scenario testing, all include both data testing and software testing.

In parallel testing, data-driven testing is performed through the automation of data injection methods, while software-driven testing adopts an experience-enhanced automated testing method. The former focuses on the consistency between manual system data and real system data in various scenarios, while the latter focuses on the stability of software updates.

In the data testing scenario, due to the large amount of real-time data exchange between the CTC equipment and various systems, data-driven scenario generation is used to verify data accessibility. Specifically, we verify whether the phase plan issued by the dispatch center can automatically generate train route instructions that can be accurately sent to the computer-based interlocking equipment to operate the field signal equipment.

We take the CTC system import table and the interface data testing as an example to introduce the data-driven testing scenario generation method. The automated testing system consists of a testing management terminal, a CTC autonomous unit, and a computer interlocking simulation system. The data testing management terminal is the core part of the distributed autonomous dispatch central station, mainly composed of a testing case automatic generation module, a case execution and validation module, an automatic report generation module, a communication module, a testing playback module, and a human-machine interaction module. The testing case automatic generation module outputs testing cases by reading the autonomous unit's route files and interlocking queue mapping files, and can classify testing cases and generate testing data verification content. The generated testing cases and verification content can be regenerated after the configuration file is modified. The design principle of the autonomous unit data testing system does not change the connection of the CTC station autonomous unit's external interface and the existing information forwarding logic. The CTC autonomous unit is used to run as the testing object, and the computer interlocking simulation system is used to receive control commands from the autonomous unit and return the yard change and complete station representation information.

In the software testing scenario, we adopt an experience-enhanced scenario generation method. The method enables us to test whether the internal logic of the software conforms to expectations by fully traversing all software functions, thus quickly verifying its reliability.

We apply the data playback approach and utilize the historical data of train operation dispatching. By cleaning, analyzing, and mining the data, we extract the key feature set data for automated testing and realize automated testing of CTC systems based on parallel systems. The designed backend program for automated regression testing consists of the testing management terminal, the tested CTC system's backend program software, and the testing data that includes detailed logs. The automated regression testing management terminal is the core module. It completes human-machine interaction and various testing management functions, loads relevant automated testing log script files, and inputs the current testing case to the tested CTC system's backend program for testing. After the testing, the module compares the data recorded by the tested CTC system's backend program log module with the relevant automated testing log script files according to consistent comparison rules. The testing result of the current testing case is determined based on the comparison result.

E. CTC Scenario Testing via Virtual-Real Interaction

CTC parallel testing combines virtual testing and field testing based on the generated scenarios, achieving comprehensive testing of the CTC system. The closed loop of parallel testing mainly includes two parts.

First, various independent and combined scenarios are generated to perform large-scale virtual testing on the modules and subsystems of the CTC system. The principle of scenario generation is to ensure the completeness of the scenario, to achieve comprehensive testing of all modules, and to verify the robustness and stability of the system as a whole. On the other hand, under the premise of ensuring comprehensive testing, challenging scenarios are emphasized, which specifically target possible weak modules of the system.

In virtual testing, scenario-based uniform sampling and importance sampling methods are used to generate comprehensive scenarios and challenging scenarios, respectively. Uniform sampling selects the sample points of the scenario parameters uniformly based on the parameter space defined in the scenario description to cover all testing scenarios. For some safety-critical scenarios and scenarios with a small number of parameter combinations, we will traverse all scenario parameters. For some scenarios with a large number of parameter combinations, it is difficult to complete testing of all scenario parameters in a limited time. Therefore, we first cover all scenario parameter distributions through uniform sampling and evaluate the system performance, and then use the scenario importance weights constructed based on the system performance evaluation results and human experience to perform importance sampling. This method aims to generate more key testing scenarios for weak links in the system and guides the automated testing system to generate more key testing scenarios based on human experience.

The two characteristics of virtual testing make the testing process more efficient and reliable: 1) Virtual testing allows us to conduct large-scale computational experiments in parallel, accelerating the testing process of the CTC system. We have built a distributed system that can generate concurrent scenarios, i.e., testing multiple sets of parameters at the same time, greatly improving the testing efficiency. 2) Virtual testing allows us to flexibly generate various critical and challenging scenarios by setting external factors. For example, we have constructed cases of network attacks and data tampering to test the communication module's robustness (interference resistance) of the CTC system. We have also generated various extreme climates and weather conditions to test the security and reliability of the CTC system. Virtual testing enables us to comprehensively evaluate the performance of the CTC system before field testing and to make timely system optimizations.

Next, we conduct parallel testing of virtual and real-world scenarios. In this phase, field testing mainly focuses on the reliability of the CTC in the real system, while virtual testing is based on field testing and generates more similar scenarios to synchronously test the corresponding artificial CTC system.

Parallel testing constitutes a closed loop of the model and data. For the model loop, it includes field testing and virtual testing of the system model. In field testing, the scenario generation process adopts the virtual testing-guided scenario generation method. Uniform sampling is used to generate testing scenarios that cover all functions to ensure comprehensive testing. In contrast, important sampling based on the virtual testing process is used to generate some challenging scenarios to accelerate the generation of critical scenarios and improve field testing efficiency. At the same time as field testing, we also conduct virtual testing, which generates more scenario parameters under the field testing scenario parameters to test the artificial CTC system. In other words, one field testing in the real system corresponds to multiple tests in the artificial system, and this testing process is parallel, thereby improving testing efficiency. The system model can conduct parallel testing in real and artificial systems, which can quickly discover problems and drive continuous iterative optimization of the CTC system.

The data closed-loop is aimed at the calibration of the artificial system, i.e. the alignment between the artificial system and the real system. In field testing, we continuously collect on-site data and update the artificial CTC system and the testing system to improve the fidelity of the artificial system. This data loop ensures that the artificial system constantly approaches the real system and further enhances the reliability of virtual testing.

After testing in the real system, scenarios that did not pass can be returned to the first step of virtual testing for comprehensive testing. Based on this, through continuous iterative virtual and real interactive testing, we can ensure comprehensive testing while accelerating the efficiency of generating critical scenarios and assisting in improving the performance of the CTC system, making the CTC system highly secure and reliable in both the artificial and real worlds.

F. CTC Performance Evaluation

In order to comprehensively evaluate the performance of the CTC system, we use the scenario pass rate as the performance evaluation metric, which is applicable to any testing scenario, including independent testing scenarios and comprehensive testing scenarios.

The discrimination of the scenario pass rate adopts an experience-enhanced automatic discrimination technology, which builds a historical experience library to generate the expected results of the testing scenarios. We can achieve objective, accurate, and fast judgment for CTC systems by automatically comparing the system testing results with the expected results and judging whether the system functions meet expectations.

The process of the experience-enhanced testing performance evaluation method is as follows. First, we initialize the automation testing tool and set the consistency comparison rules of the testing tool according to the experience-enhanced memory bank. In the rules, time difference and content difference thresholds corresponding to specific information types are set based on testing experience. Then, we load the testing scenario script (including program configuration, log files, and expected results), conduct scenario testing, and record the testing results of the tested object. Finally, the threshold method is used to compare the consistency between the testing results and the expected results. When their difference is less than the threshold, the scenario testing is considered passed; otherwise, it is considered failed.

In the performance evaluation process based on experience-enhanced techniques, careful consideration is needed when selecting thresholds. Based on the experience-enhanced theory, we establish an experience memory bank via a large amount of historical data or the historical optimal solution of a model, and formulate comparison rules. Thresholds are set for specific information types in the rules. When the original data and the testing data are completely consistent or the difference does not exceed the threshold set by the comparison rules, the automated testing is still considered to have passed; otherwise, the automated testing case is considered to have failed. The experience memory bank includes three aspects:

1) Time difference threshold: Due to factors such as the operating system, CPU clock frequency, and disk read and write performance, there may be minor differences in the testing output results and the original data, although they are exactly the same. In this case, we set the time difference threshold for specific information types. For the same data content, if the sending and receiving times are within the time difference threshold, the testing is still considered to have passed.
2) Information content difference threshold: Due to reasons such as software updates or operating system upgrades, there may be minor differences between the testing output results and the original data. These minor differences are often unrelated to the logic and are mostly due to differences in text or symbols, spaces, etc. In this case, we set the content difference threshold for specific information types. If the difference is within the content difference threshold, the testing is still considered to have been passed.
3) Information quantity difference threshold: Due to issues such as system clock errors, periodic output results related to sent and received information may not be consistent with the original data, showing that the testing results have more or less piece of information compared to the original data. In this case, we set the information quantity difference threshold for specific information types. If the difference is within the quantity threshold range, the testing is still considered to have been passed.

In the parallel testing process, we comprehensively evaluate the various functional modules of the CTC system based on the scenario pass rate, and use the evaluation results to find challenging scenarios. This process helps enhance the ability of the CTC system to respond to various critical scenarios.

IV. Beijing CTC Parallel Testing Systems: A Case Study

In this section, we showcase the practical application of the Beijing CTC parallel testing system on the Beijing-Tianjin HSR. The Beijing-Tianjin HSR serves as a crucial link between Beijing and Tianjin, spanning 166 kilometers. It is the first high-standard HSR in mainland China, designed to operate at a speed of 350 kilometers per hour. This railway line sets high standards for the safety, reliability, and efficiency of the CTC system.

We demonstrate how parallel testing, through a closed-loop virtual-real testing approach based on scenario engineering, ensures that the CTC system maintains high performance levels. Specifically, the operational process and results of the Beijing CTC parallel testing system will be presented. The operational process is exemplified by the comprehensive scenario testing of schedule-based train routing. The operational results showcase a comparison of costs between parallel testing and manual testing in the interface, S&C, and transportation scenarios. The experimental results clearly indicate that parallel testing methods improve testing efficiency by nearly 50% compared to traditional manual testing methods. These detailed experimental results illustrate that parallel testing outperforms traditional manual testing methods in terms of testing efficiency, cost reduction, and workload reduction for various scenarios in CTC systems. Consequently, the safety and reliability of the HSR system are ensured.

A. *Operational Process of Beijing CTC Parallel Testing Systems on Schedule-Based Train Routing*

The Beijing CTC parallel testing system is a way to evaluate S&C systems without interfering with train operations, using software-defined artificial HSR systems. The system uses various simulated traffic scenarios to imitate the genuine operation of a train and the functioning of the S&C system, providing thorough testing and assessment of the S&C system. The development and implementation of this testing system is broken down into three stages: constructing the artificial system, outlining and producing the scenario, and linking the real and artificial worlds for parallel testing.

We have employed object programming and agent technology to construct an artificial HSR system modeled on the Beijing-Tianjin HSR. This artificial system replicates multiple stations, trains, and control centers as agents with distinctive qualities and autonomous decision-making capacities. By combining the efforts of these agents, we can devise numerous rapid railway operation scenarios. This article considers three different scenarios: the interface scenario, the S&C scenario, and the transportation scenario. Almost all aspects of CTC testing are encompassed by these three scenarios, incorporating testing objects, both physical and simulated systems (CTC centers, railway stations and on-board train equipment), personnel, and external influences like the environment and topography. We can carry out a variety of repeatable computational experiments in these scenarios, such as gauging operating system consistency, controlling policy measurement, and assessing responses to emergency events.

The agent-based artificial system we construct has more comprehensive modeling features than traditional simulation, encompassing modeling explanations from macro, meso, micro to logical levels. At the macro level, we construct train stations and bridges that accurately reflect their real locations, and also draw the line topology corresponding to the station yard type. This yard station is able to replicate the operation of 12 trains in parallel, including 10 stations and 5 dispatching segments (refer to Fig. 4). We set up a S&C apparatus that includes signal machines, transponders, and turnouts along the track configuration according to meso-level requirements. Simultaneously, we develop relay logic to reproduce the genuine operation of trains in the dispatching division, which is in line with

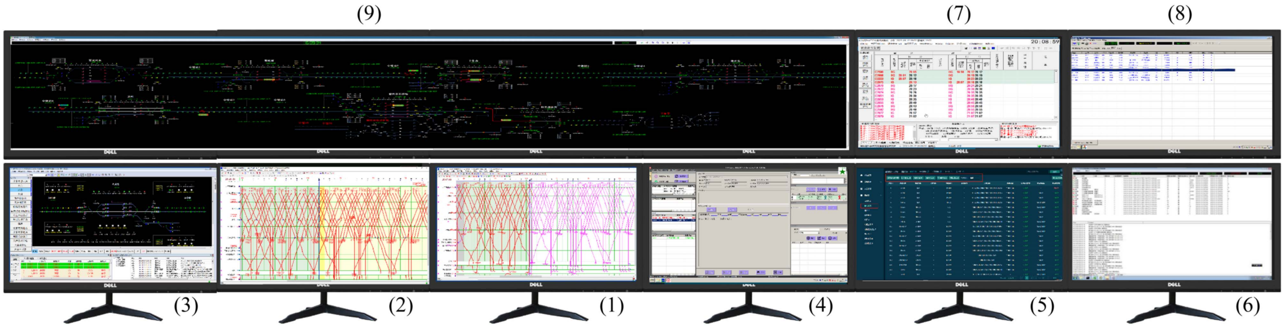

Fig. 4. Display of parallel testing for schedule-based train routing. The functional modules include: (1) train timetable terminal; (2) train timetable query terminal; (3) assistant dispatch terminal; (4) dispatch command terminal; (5) testing monitoring terminal; (6) application server; (7) train operation terminal; (8) train simulation and monitoring; (9) section panorama display.

the signal machines and turnouts configured in the scenarios. This enables the artificial system to continuously form train occupancy, clearance, and signal shutdown states, and to model code displacement behavior within stations and between sections, thereby constructing the framework for the train operation system.

After the artificial system is established, we use it to produce whole train operating scenarios based on the variables of three distinct testing scenarios. This enables us to design complicated scenarios for free combinations depending on the combination of the variables from the three testing scenarios. Additionally, the system can be used to describe and build these scenarios in detail, providing a comprehensive panorama of the procedures. Among them, the interface scenario focuses on the data transfer logic between the system components, the S&C scenario ensures that the dispatching center's manual controls are operational, and the transportation scenario is a dynamic assessment of the CTC capabilities of the dispatching center.

With the scenarios established, we deploy the parallel testing systems for schedule-based train routing functionality testing. The overall display of parallel testing systems is shown in Fig. 4 and the deployment workspace is shown in Fig. 5. The parallel testing process is as follows:

1) Create and disseminate stage plans. Dispatchers change the operational chart to create a train schedule that is accurate, feasible, and safe for passengers. They take into account factors such as train quantity, station capacity, and travel speed, and use computer simulations and real-time data monitoring to generate optimal plans and address issues during train operations. Once created, the plan is approved and examined by the station testing duty officer at the train service terminal. Continuous optimization of stage plan generation and issuance can boost train efficiency, safety, and passenger experience.
2) Check the train approach sequence. After dispatchers issue the phase plan, the CTC system's train service terminal displays train approach information. The testing station duty officer verifies the accuracy of this information for each train. The approach sequence is color-coded, with yellow indicating that the station auto-triggers have not been activated, green indicating successful transmission of approach command data, and gray indicating a completed strategy. Testers should ensure the accuracy of any changes made in the order of steps.
3) Verify the timing of the train approach trigger. To ensure efficient train operations, the timing of train approach triggers must be checked by comparing the actual arrival of trains with the expected time established during simulation scenarios. Any discrepancies must be addressed promptly to keep train operations on schedule and ensure passengers

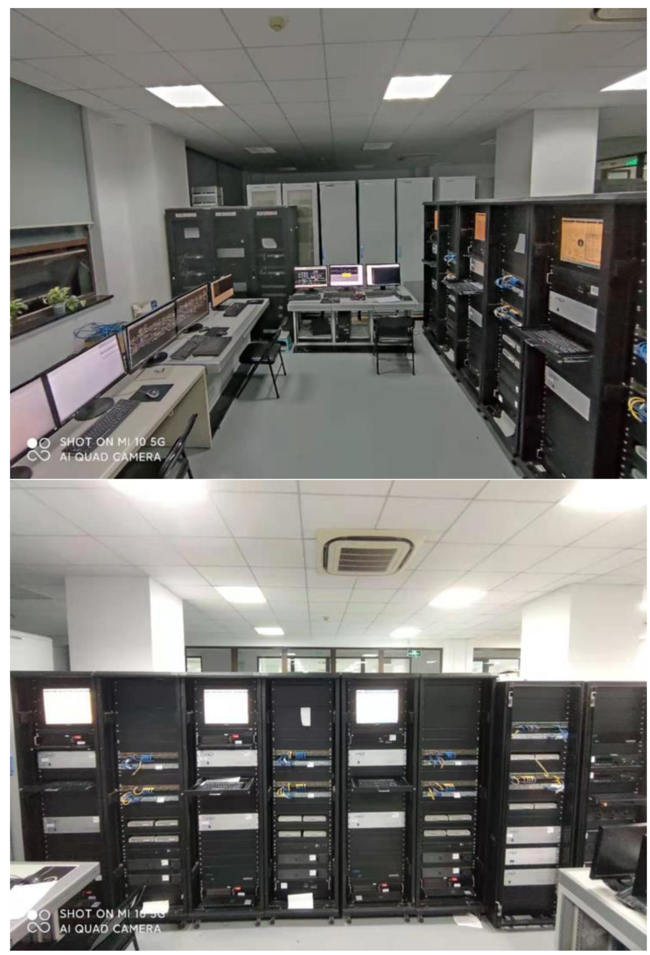

Fig. 5. Deployment workspace of CTC parallel testing systems.

arrive on time. Continual improvement of the timing check process can enhance train operations and provide a better travel experience for passengers.

4) Monitor the train approach process. The CTC system prioritizes passenger trains over cargo trains according to the SODR map. Trains scheduled for halt are assigned higher priority than those designated for pass-through. The starting train approach is triggered first, followed by the receiving train approach. The driver is notified via radio and the examiners ensure that all criteria are met during the train arrival.
5) Confirm the correct track for the overrunning train pick-up. The testing dispatcher flags the train as an over-restricted train and verifies that the station autonomous computer is connected to the correct stock path according to the SODR. This verification process ensures the safe and accurate traversal of the train through the station, avoiding potential safety issues or delays.
6) Verify the permissibility of simultaneous pick-up and send-out at the station. Passenger trains must adhere to SODR regulations for passage, with simultaneous pick-up not permitted to disconnect the end of the pick-up line from the equipment. If the inbound direction of the signal machine has decreased by more than 6% beyond the braking distance, simultaneous pick-up and send-out in the same direction is not permitted. To prevent automated handling, the station regulator will intervene, and testing staff will have to monitor and inspect the process.
7) Test train operations. During a comprehensive train operation testing, a diverse array of trains follows a meticulously laid-out plan. When a train departs, the designated access route is automatically activated, and the CTC tracking system transmits the point data to the dispatch station. The received data are quickly processed and converted into a detailed operational route map displayed on the CTC monitor. The map shows critical information such as the train's current speed, driver identity, and route length, enabling efficient train management and increased safety and punctuality.

Using the parallel testing method, we can assess the performance and dependability of the CTC system, identify potential issues or flaws, and take swift corrective action. Implementing the testing system does not disrupt train operations, which enhances the precision and speed of testing and ensures the reliability of S&C systems and the security of HSR lines.

B. Operational Results of Beijing CTC Parallel Testing Systems on Scenario Validation

The Beijing CTC parallel testing system is designed for comprehensive functional testing of the CTC system, such as schedule-based train routing. The testing scenarios are divided into interface scenarios, S&C scenarios, and transportation scenarios. Fig. 6 showcases the user interface (UI) and the testing site for these three scenario tests. These fundamental scenario tests constitute a panoramic view of the testing process, allowing for a comprehensive evaluation of the safety and reliability of the CTC system. Next, we present the time and cost spent in parallel testing versus manual testing for three scenarios. The experimental results validate that parallel testing outperforms manual testing methods in terms of testing efficiency, cost reduction, and workload reduction.

Fig. 6. Parallel testing in practical engineering: Interface scenario testing, S&C scenario testing and transportation scenario testing.

1) Interface Scenario Testing: Interface testing involves verifying the interface data between the CTC system and downstream devices from different manufacturers. It focuses on testing the inputs and outputs of the application's API to ensure that they meet requirements and specifications. In the inference testing depicted in Fig. 6, we present the detailed UI of the testing system. The first row, from left to right, includes the interlocking simulation system and manual operation agent, the server management platform, and the server-side human-machine UI. The second row, from left to right, shows the UIs of interlocking simulation systems, the execution status of CTC systems, and the display of testing results. Table I presents the testing items, the testing contents, and the time required for both manual testing and parallel testing in the interface scenario. The testing station contains 9 tracks, 42 switches, 60 signals, and 600 routes. The experimental results indicate that in the interface testing scenario, such as verifying interlocking route tables, switch data and section data, parallel testing improves testing efficiency by approximately 50% compared to manual testing. This demonstrates that parallel testing can greatly reduce manual workload and improve work efficiency in interface scenarios.

2) S&C Scenario Testing: S&C testing aims to verify the correctness, reliability, and safety of the railway signaling systems. It ensures that the control functions of the dispatching center are

TABLE I
COMPARISON BETWEEN PARALLEL TESTING AND MANUAL TESTING IN INTERFACE SCENARIOS

No.	Testing Item	Testing Content	Manual Testing Time	Parallel Testing Time	Saved
1	Environment Setup	Interlocking environment and CTC environment setup	$\approx$ 1 h	$\approx$ 24 min	**60%**
2	Switch Verification	Switch operation and consistency	$\approx$ 250 min	$\approx$ 125 min	**50%**
3	Derail Verification	Derail state operation and consistency	$\approx$ 270 min	$\approx$ 135 min	**50%**
4	Signal Verification	Consistency between CTC and CBI signals	$\approx$ 415 min	$\approx$ 208 min	**50%**
5	Route Button Verification	Button operation and consistency	$\approx$ 75 min	$\approx$ 37.5 min	**50%**
6	Section Verification	Section state operation and delay display	$\approx$ 335 min	$\approx$ 167.5 min	**50%**
7	Route Verification	Consistency between route instructions and display	$\approx$ 2000 min	$\approx$ 1000 min	**50%**

TABLE II
COMPARISON BETWEEN PARALLEL TESTING AND MANUAL TESTING IN TRANSPORTATION SCENARIOS

No.	Testing Item	Testing Content	Manual Testing Time	Parallel Testing Time	Saved
1	Schedule Drawing	Draw testing train operation schedule	$\approx$ 50 min	$\approx$ 25 min	**50%**
2	Route Instruction Verification	Check route instructions via train operation schedule	$\approx$ 300 min	$\approx$ 150 min	**50%**
3	Station Detail Condition Check	Check the conditions in the SODR	$\approx$ 300 min	$\approx$ 150 min	**50%**
4	Train Tracking Simulation	Simulate train operation and light band changes	$\approx$ 1500 min	$\approx$ 900 min	**40%**

intact and implemented according to the operator's intentions. In the S&C scenario testing depicted in Fig. 6, we showcase the S&C testing center, the train station, and the equipment room for verification purposes. During S&C testing, we combine inference testing and transportation testing to improve testing efficiency. Parallel testing methods assist human operators in better examining the consistency between on-site equipment displays and operational consistency. In the route trigger and speed restriction testing, as well as in the SODR testing, experimental results indicate that parallel testing improves the testing efficiency by approximately 30% compared to manual testing.

3) Transportation Scenario Testing: Transportation testing focuses on ensuring the safety and functionality of transportation systems, such as railway infrastructures, rolling stocks, and signaling systems. The testing process evaluates various aspects of the transportation system, including train scheduling, route planning, and control systems, using software to test the system's ability to handle different situations. In the transportation testing depicted in Fig. 6, we present the entire process of its operation. First, we lay out the artificial train operation lines on the dispatching workstation. Then, stage plans are issued to the artificial autonomous dispatching system and the train terminal. Subsequently, we verify the plans at the train terminal during the sign-off stage. Finally, the signal simulation system automatically generates simulated train operations based on the plan, verifying the route triggering conditions. Table II presents the testing items, testing contents, and the time required for manual testing and parallel testing in the transportation scenario. The experimental results indicate that in the transportation scenario, such as route instruction verification and SODR checks, parallel testing improves the testing efficiency by approximately 50% compared to manual testing. This demonstrates that parallel testing significantly enhances testing efficiency and reduces the time and resources required for transportation testing.

V. CONCLUSION

This article proposes a parallel testing method for CTC systems and verifies it on real railway systems in numerous cities within China. Through the scenario-based representation and interaction of virtual and real testing, parallel testing improves the efficiency of critical scenario validation while ensuring comprehensive evaluations. The deployment of parallel CTC testing systems reduces the workload of S&C workers, and improves the efficiency of on-site construction and transportation organization, as well as the stability and reliability of CTC systems.

In the future, we plan to apply the latest AI technology, such as large language models (LLM), to CTC testing. This will enable us to build a new paradigm of parallel testing, where humans and corresponding digital entities are actively involved in the loop. Human expertise in system testing will be digitized and incorporated into automated testing processes through foundation models, achieving intelligent testing of CTC systems in terms of comprehensive elements and processes. Additionally, human feedback on system testing will be utilized to facilitate autonomous upgrades of CTC systems.

Ultimately, our goal is to achieve the 6S objectives of CTC systems: safety in the physical world, security in cyberspace, sustainability within the HSR ecosystem, sensitivity to data privacy and rights, service excellence, and smartness aligned with human values [55], [56].

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