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Retraction Notice

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Modeling and Simulation of China Railway High-Speed Electric Multiple Units Based on Multi-Agent

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Abstract

China Railway High-speed (CRH) has been developing rapidly in recent years and enjoying a great reputation throughout the world. China has achieved independent innovation and leapfrog development of high-speed rail technology through technology introduction, digestion and absorption. Many methods have been used in the research process of CRH Electric Multiple Units (EMU). Modeling and simulation is one of the most effective and economical methods. However, the traditional method for simulation modeling has been difficult to be applicable because of the complex structure, numerous entities, complicated interactions and the emergence of large-scale complex systems. In this paper, we have applied the multi-Agent-based modeling and simulation technology to the research on CRH EMU. Meanwhile, we have developed a new simulation platform for this research in order to launch more virtual experiments. Through the analysis of simulation result data, it is proved that the method of multi-Agent-based modeling and simulation is practicable. This has promoted the development of CRH EMU to some extent.

Keywords

Multi-Agent, CRH, EMU, Modeling and Simulation

1. Introduction

In recent years, high-speed railway has been developing rapidly in China. By the end of 2018, China's high-speed railway has had its operation mileage over 29,000 kilometers, accounting for more than two-thirds of the world's high-speed railway operation mileage and exceeding the total of other countries [1]. With regard to

EMU, China has jointly designed and manufactured high-speed EMU by introducing technologies from Bombardier of Canada, Kawasaki Heavy Industries of Japan, Alstom of France and Siemens of Germany. These EMUs are named CRH1/2/3/5. Through studying foreign advanced technology, China hopes to ultimately realize independent innovation and leapfrog development of CRH technology. After years' research, China has systematically mastered the technology for manufacturing 200 - 350 km/h EMU and developed and manufactured CR400/300/200 series of new generation EMU subject to Chinese standards.

Moreover, high-speed EMU is rather complex in structure and its power bogie alone contains more than 2000 parts. The design and development of these parts also involve many different fields and disciplines, including machinery, dynamics and control science, etc. It is difficult to verify the system effectiveness as quickly as possible through the process of designing and manufacturing a prototype of EMU, which is time-consuming and laborious. Therefore, technique of modeling, simulation and virtual prototype of EMU can provide a feasible, credible and economic means for the design and research. The authors' research team participated in the digestion and absorption of the key technologies in the high-speed CRH5 of Alstom, France. They helped to design CRH5-based long-marshalling high-speed EMU by using simulation modeling and virtual product development technology, which has further shortened the research and development time. This technology reduced the cost and improved the reliability.

CRH EMU system is a complex large system, featuring massive components, complex structures, complicated behaviors and interactions between elements, and especially the obvious system emergence. For such systems, we should not only simulate its normal operation functions, but also simulate its performance in abnormalities, failures and incorrect operations. Therefore, it is difficult to get the solution of the problem through top-down analysis and we cannot completely use the simulation method based on discrete events. Thus, according to these characteristics, this paper has applied the multi-Agent-based simulation technology [2] to EMU research and introduced the simulation of train drivers' working status.

Multi-Agent-based simulation is a technology in the field of artificial intelligence [3]. It refers to the computing entity that can play a continuous and autonomous role in the dynamic environment and has the characteristics of initiative, responsiveness, autonomy and sociality. Compared with other simulation technologies, multi-Agent-based simulation has many advantages [4]:

1) Agent has the ability of self-perception and cooperation.

2) Agent has the ability of autonomous solution and runtime decision-making.

3) Agent has the ability of interacting with users.

4) Agent has flexible organizational framework and evolutionary mechanism.

It provides a brand-new and efficient solution for the analysis and simulation of such complex large-scale systems.

2. Modeling of CRH EMU

The CRH5 EMU designed by French Alstom is a power dispersed and AC-drive EMU consisting of five EMU and three trailers (as shown in Figure 1), in which MC1, MC2, M2S, M2 and MH are EMU equipped with power bogies. TP, T2 and TPB are trailers equipped with non-power bogies.

China intends to research a long formation high-speed EMU consisting of 16 coaches based on CRH5. Long formation high-speed EMU is a typical complex product. Its geometric design model is easy to get, but the dynamic performance such as traction, braking and curve crossing will inevitably change greatly. Therefore, this paper will focus on the dynamic performance simulation of CRH5. On the one hand, it can further reflect the design concept of Alstom EMU, and play a guiding role in the research. On the other hand, it can reuse these simulation models in the development process of other types of EMU in order to improve the efficiency.

The whole simulation system consists of eight coaches, seven couplers and draft gears (CDG) between coaches, sixteen bogies, train control system and driver. The simulation system will comprehensively consider the effects of mechanical, control, dynamics, personnel control and other aspects on the overall performance of high-speed EMU, such as carrying capacity, running stability, ride comfort, curve passing performance, safety indexes (including derailment coefficient, load reduction rate, wheel-rail transverse force, wheel-axle transverse force and overturning coefficient) and so on. Based on the simulation platform we developed, we can realize the multi-disciplinary modeling and collaborative

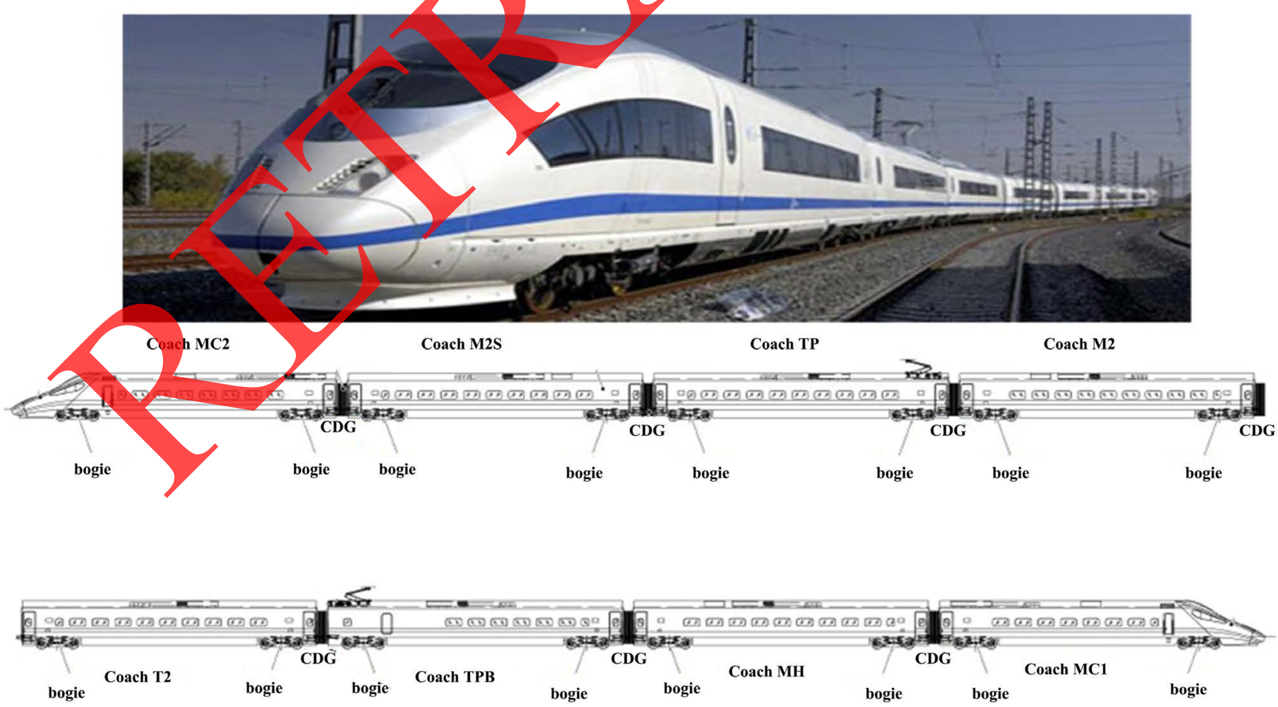

Figure 1. Vehicle body of CRH EMU.

simulation, and carry out such simulation analysis of great engineering significance, such as coupler cushioning characteristics, EMU lateral stability (critical speed), start/brake performance analysis, comfort evaluation, dynamic limit analysis and emergency state (air spring loss). Here we take the headstock, middle coaches, tailstock, bogie, CDG and driver as examples to illustrate how to establish the simulation model.

2.1. Multi-Disciplinary Simulation Modeling

1) Firstly, use Automatic Dynamic Analysis of Mechanical System (ADAMS) [5] software to establish the dynamic models of the headstock, tailstock, middle coaches and bogies (as shown in Figure 2). As a high-precision and efficient modeling and simulation software based on multi-rigid-body dynamics and vehicle system dynamics, ADAMS/Rail can fully simulate the kinematic and dynamic characteristics of vehicles. The complete vehicle model built by ADAMS/Rail features a high degree of freedom and its model parameters are easy to revise and debug, with the specific modeling process as follows:

a) Use ADAMS to build the mechanical model of the simulation system and add external loads and constraints, generally through the transformation of CATIA (Computer Aided Three-dimensional Interactive Application) model.

b) Use MATLAB/Simulink to build the control part model of the mechanical simulation model.

c) Use ADAMS/Controls (control module) to match the two models effectively. First, use the control output of MATLAB/Simulink to drive the mechanical model and feedback the displacement, speed and other outputs of the mechanical model in ADAMS to the control model. Therefore, we can realize the interactive simulation in the software environment of the control system. Moreover, the simulation results can be checked in ADAMS/View or ADAMS/Solver.

2) Establish the control model of a CDG in the MATLAB environment, use

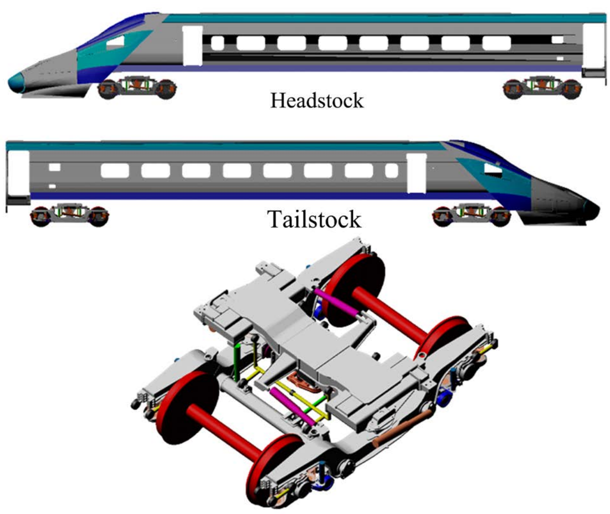

Figure 2. ADAMS models of headstock, tailstock and bogie.

MATLAB to model and simulate the coupler buffers between 1st and 2nd, 2nd and 3rd, 3rd and 4th as well as 4th and 5th coaches, and simultaneously build Agent-based middleware. At present, high-speed EMU widely use DellNer CDG. According to DellNer's working principle and hysteretic characteristic curve, the CDG can be regarded as a special longitudinal suspension with variable stiffness and damping. The equivalent MATLAB model of CDG for simulating coupler buffer characteristic curve is shown in Figure 3.

3) Establish the bodywork dynamic model in the Vampire environment, as shown in Figure 4. Use Vampire to model and simulate the whole model of the rear four coaches.

4) Establish the finite element analysis model of the bogie framework in the ABAQUS environment, as shown in Figure 5. Use ABAQUS to carry out stress and strain analysis of the framework elements in bogies.

2.2. Agent Model Transformation

According to the dynamic model of high-speed railway EMU, it can be transformed into the corresponding Agent model to simulate the simulation of each component Agent under different parameters and working conditions. Each type of Agent should contain the following definitions [6]:

1) Define the simulation clock.

2) Define the set of input messages, including external input and internal feedback input.

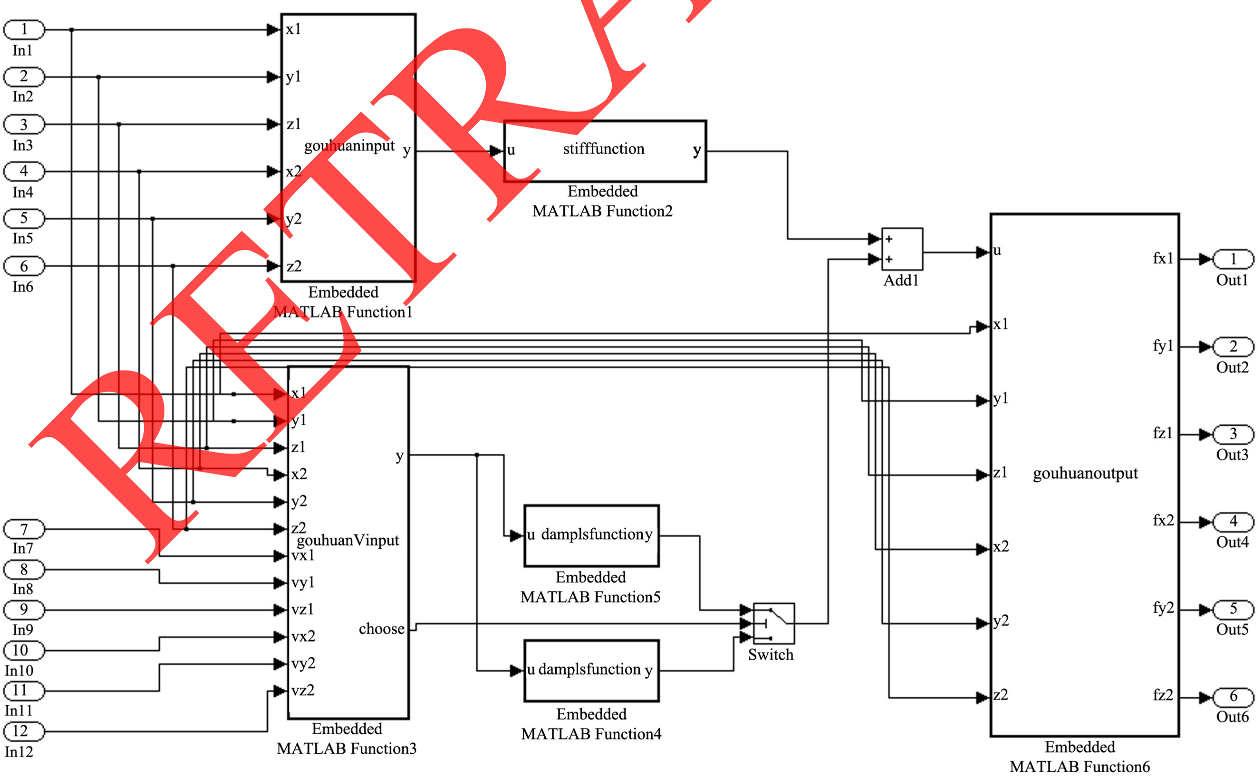

Figure 3. Matlab model of CDG.

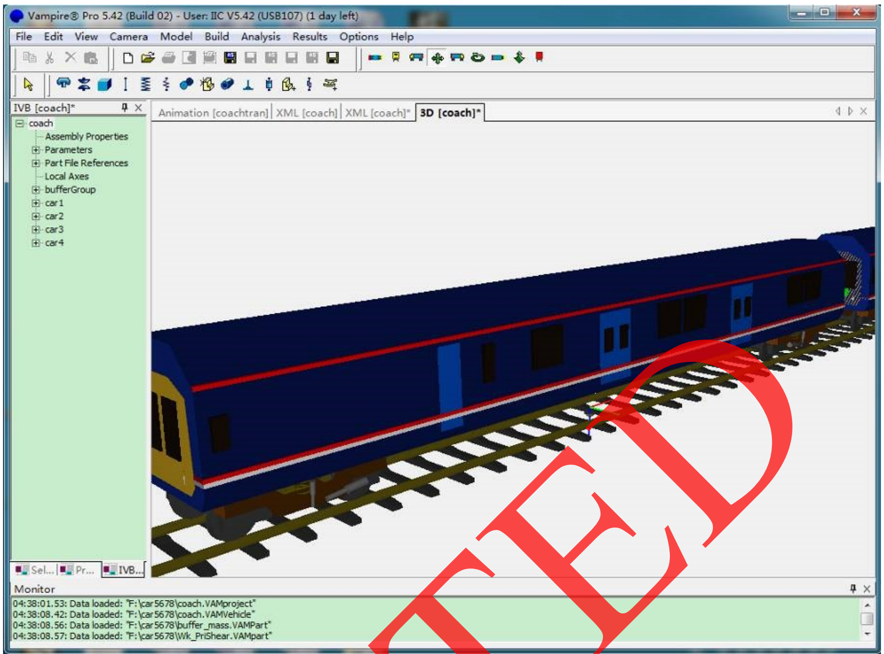

Figure 4. Vampire model of four coaches.

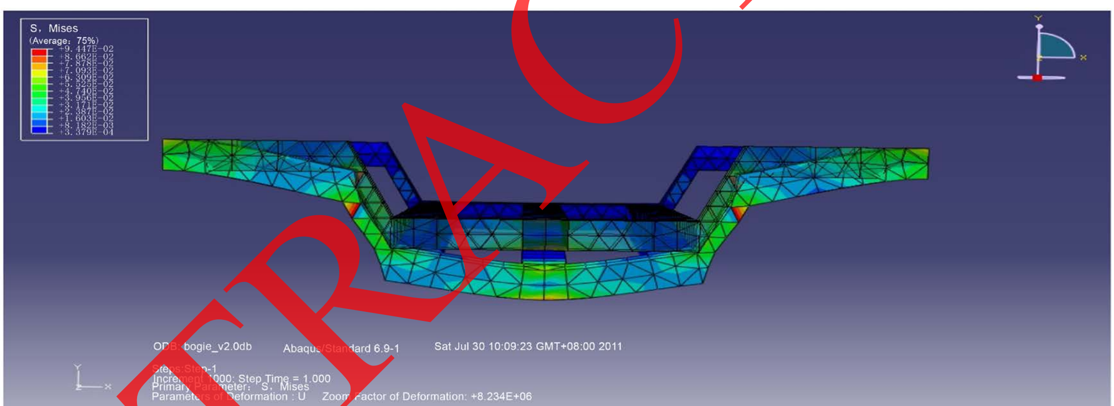

Figure 5. Vampire model of four coaches.

3) Define the set of output messages.

4) Define the set of states.

5) Define the control rule base and controller algorithm, including rule generation, rule selection and rule evaluation algorithms.

6) Define the set of input source Agents and indicate which Agents the external input comes from.

7) Define the set of output source Agents and indicate the set of the destination Agents for message output [7].

8) Define message generation algorithms.

Based on the function of the ADAMS/Controls module, the ADAMS and MATLAB models can be encapsulated according to the Agent specifications and hide the technical details of model implementation. In this way, after the initial parameters of simulation has been defined, each Agent can work autonomously and plug-and-play imitation can be achieved, which is more flexible than HLA-based simulation.

See the following steps for Agent compatibility modification against the ADAMS model:

1) Establish a mechanical system model of ADAMS [8]. The mechanical model can be established directly under ADAMS, or we can use the interface between ADAMS and other CAD/CAE software to input a built external model.

2) Determine the ADAMS model input and output variables and the set of internal states, and define the state transition rules. Use the ADAMS/Controls module to output ADAMS data files (.adm files) and MATLAB model files (.m files).

3) Construct an Agent API model of the ADAMS and MATLAB models in the Agent-based simulation environment; read or receive ADAMS and MATLAB input and output variables to drive these models to work.

4) Construct control rule, state and message bases in the Agent transformation model to automatically respond to various inputs and achieve various controls.

5) Construct a driver Agent model, able to simulate the operation instructions issued by human and thus drive the whole simulation model to work. At the same time, construct a human reliability model to simulate the probability of human incorrect operation in terms of long-term fatigue driving and thus verify driver's longest working time and the fault-tolerant treatment of the train control system under the condition of driver's incorrect operation.

6) Construct a data acquisition Agent, collect the intermediate data generated in the process of simulation and thus make statistical analysis.

The deployment architecture of the whole simulation is shown in Figure 6. All models are developed based on JADE (Java Agent Development Framework) [9]. JADE is an open source software platform that can provide basic middleware functions. Currently it is widely used. As a fully distributed middleware system with flexible infrastructure, JADE can provide a real-time running environment, able to implement the essential functions of an Agent throughout its life cycle and the core logic of the Agent itself. Moreover, it can establish the

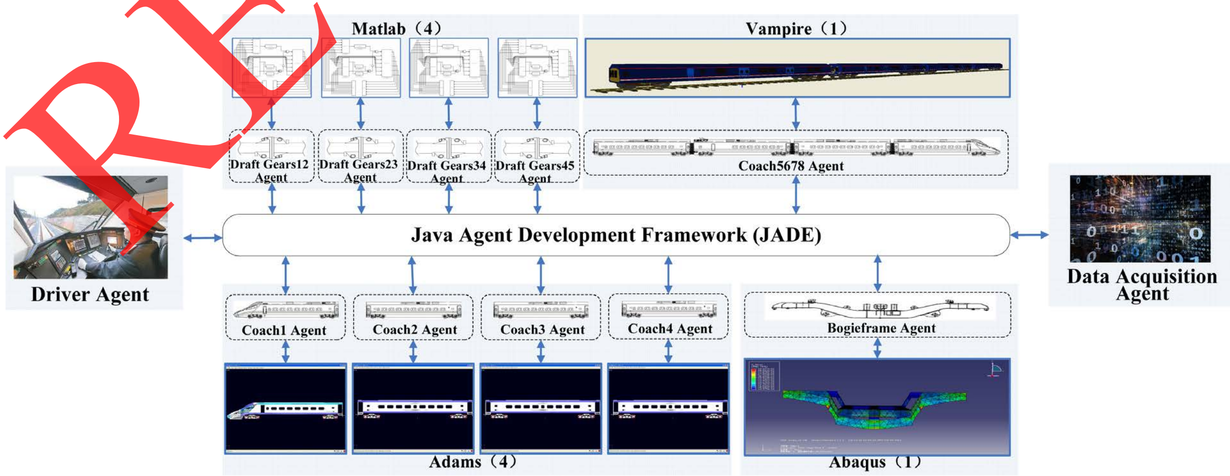

Figure 6. Simulation deployment based on JADE.

functions and attributes of each kind of Agents and the communication mechanism between Agents according to the characteristics of entity objects, without concern for the underlying physical implementation.

3. Simulation of CRH EMU Based on Multi-Agent

3.1. Systematic Architecture

Modeling and simulation of CRH EMU based on multi-Agent has general characters of the system. Firstly, the construction of the Agents and other simulation models in the CRH EMU is the key factor of the system operation. These models simulate the properties (internal state, organizational relationships, etc.), behaviors (propulsion, communication, usage and adaptive rules, etc.) and the operating environment of component mock-up, which are driven to run a simulation in the computer by setting certain initial conditions [10]. Secondly, the operation management of multi-Agent-based simulation is also of importance. It establishes rules for Agent models interactions, communications and controlling simulation progressing, which provide a fundamental platform for simulating the mock-up operations. In this paper, the modeling and simulation framework of CRH EMU is presented and the whole systematic architecture design is illustrated in Figure 7.

Multi-Agent-based modeling and simulation of high-speed train can be divided into four layers, including simulation support layer, physical database

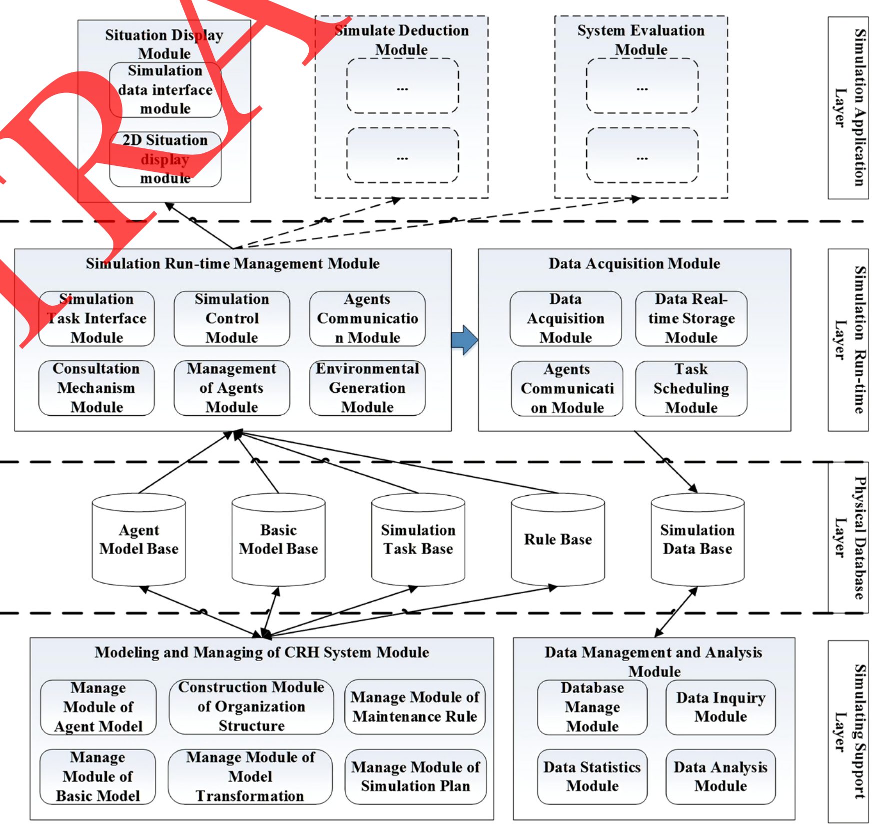

Figure 7. Systematic architecture of modeling and simulation system.

layer, simulation operating layer and simulation application layer. Simulation support layer mainly prepares for the train models and support tasks before the simulation as well as the database management, query and analysis after the simulation. The physical database layer basically stores models, support tasks and rules and simulated data appeared before and during simulation. Simulation operating layer fundamentally manages the operations in each Agent model during simulation, simulation control and real-time collection of simulated data. Simulation application layer, based on the simulated data, performs running state display, derivation of the simulation model and system evaluation.

3.2. Key Technologies

1) Simulation Run-Time Management

Simulation run-time management is the engine of the simulation system, and it is also the core of implementation, evaluation and optimization of the simulation scenario. In a macroscopic view, major functions of operation management of the simulation are as follows:

First, it creates simulation models and environments; Second, it controls the simulation process to achieve simulation synchronization and dynamic scheduling; Third, it maintains the organizational structures, interact relationship and real-time status of the EMU Agents; And finally, it enables the EMU Agents to interact internally or externally to carry out individual simulation and distributed simulation. With a large number of Agents in high-speed train, this paper presents how the simulation engine is designed to support the network topology of distributed simulation, which separates the underlying communication of the simulation from the upper-layer application. This will increase the reusability and expandability of the model while realize the Agent. A Global Service Agent, a Local Service Agent and an Interaction Agent are set in each computing node, which are used to monitor the Agent status on the node and to control Agent traffic route. This method can significantly reduce the data traffic between Agents to avoid network congestion as shown in **Figure 8**. The Agent information of the same node will be controlled within the node by means of routing [11].

2) Time Management Mechanism

As the operation of an Agent is mostly driven by events, and its internal processing mechanism features natural asynchrony, which is very suitable for modeling with distributed simulation. However, natural asynchrony drives the clock at different rates, an additional time synchronization mechanism needs to be introduced. For each Agent maintaining an internal clock, the Agent advanced its internal clock during the process of receiving and managing messages, and then marks the output messages as a time stamp with the clock value. Therefore, in the process of simulation advancement, it is essential to firstly ensure the uniformity of local clock value of each Agent, and secondly to ensure that each Agent always deals with the received messages in an incremental order of time stamp to accurately achieve causality.

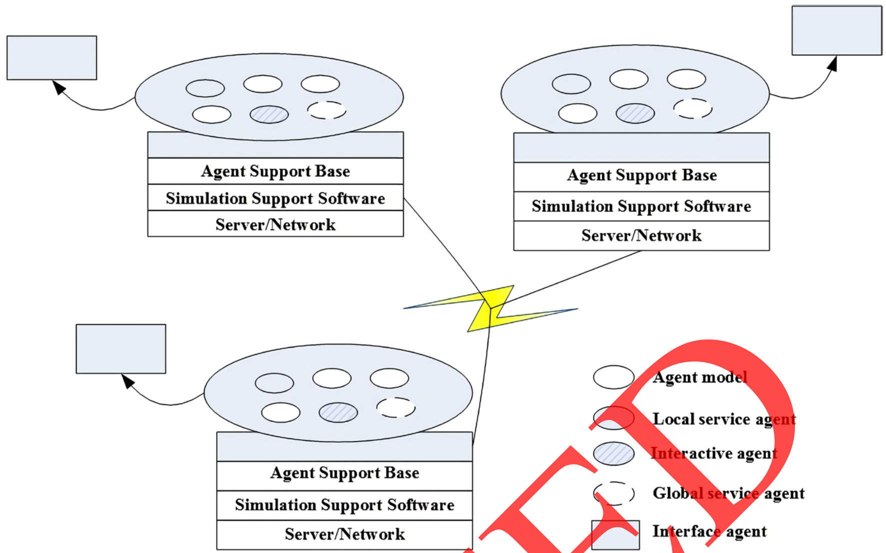

Figure 8. The strategy of interaction control between distributed nodes.

To address the first problem, it is trying to build a Global Service Agent on each network node by setting a reference time. The Global Service Agent performs the first Time Check, and then uses the heartbeat for timing. The benchmark time will not be sent to other Agents in the node until the global service Agent completes time synchronization.

To address the second problem, a corresponding time synchronization mechanism is intended to be utilized when the Agent processes messages. For now, there are mainly two mechanisms, including conservative strategy and optimistic strategy. With the conservative strategy, any causal errors will be strictly prohibited, that is to ensure that the Agent processes the received messages in chronological order. When an Agent processes an event with a time stamp T, events with a time stamp less than T will not be received. However, with empty message queue of the Agent, the processing message mechanism of the Agent is likely to be blocked, which may cause a deadlock.

The optimistic strategy allows for causal errors. The error is corrected with rollback when an error occurs. Researchers have published many conservative and optimistic strategies algorithms, which will not be discussed in this paper. As the high-speed train simulation has a distributed architecture, an integrated strategy for time management is put forward in this paper, with a conservative strategy within the node, and an optimistic strategy between nodes.

3) Data Distribution Mechanism

CRH EMU is a complex and large system involving numerous Agent elements with intricate message transmission, which may cause network congestion. In order to reduce message transmission, a publish-subscribe mode is proposed in this paper. The Agent, which delivers the message, is called the publisher. The Agent, which receives the message, is called subscriber. And the Agent, which processes the message, is called the middleware Agent. The publisher sends message to the middleware, to which the subscriber sends the subscription request, indicating what publication it is interested. The middleware sends messages with the timely, reliable and optimally matched publications and subscriptions. The publish-subscribe mode makes for a dynamic and flexible system with efficient information matching capabilities.

4. Simulation Instances and Results

With the method described above, the simulation member model of EMU is established, and the Q/P is simulated under test conditions as follows:

- Simulation parameters: dynamic simulation, simulation time 20 s, step size 0.01 s.
- Driver: set speed 20 m/s, continuous driving time 1 h;
- Track: no disturbance over the curve, the total length of the curve is 1000 m, the curve radius is 300 m, and the height is 0.150 m.
- Model: headstock, tailstock, CDG, powered bogie, no load.

The ADAMS domain model instance built by the Agent transformation software is rewritten to the ADAMS cmd file format [12], as shown in **Figure 9**.

This format is a batch file for the ADAMS system, in which the various types of modeling information needed to create a domain simulation model is included. Part of the information of each mock-up of the ADAMS can be automatically and directly imported through the model of Agent transformation, such as location information, quality information, inertia information, and simple shape information. Without modeling capability for complex model information from ADAMS, this part of information exists in the ADAMS cmd file as a file path with the performance curve files for functional parts in a specific format.

The simulation runs on the Agent-based simulation platform JADE, which manages the Agent in the form of a container on different computing nodes. The platform provides convenient Agent management, state monitoring, message

```
acar files template new &
 template_name=tttest_110925 &
 major_role=Running_Gear &
 attachment_type = single

variable set variable_name=.ACAR.dboxes.dbox_tem_har_cre.errorFlag int=0
acar template_builder hardpoint create &
 hardpoint_name=hpupper &
 location=0.0, 0.28, 1.0 &
 type=single &
 error_variable=.ACAR.dboxes.dbox_tem_har_cre.errorFlag

variable set variable_name=.ACAR.dboxes.dbox_tem_har_cre.errorFlag int=0
acar template_builder hardpoint create &
 hardpoint_name=hplower &
 location=0.0, 0.28, 1.26 &
 type=single &
 error_variable=.ACAR.dboxes.dbox_tem_har_cre.errorFlag

variable set variable_name=.ACAR.dboxes.dbox_tem_har_cre.errorFlag int=0
acar template_builder hardpoint create &
 hardpoint_name=hpbushing &
 location=0.0, 0.28, 1.29 &
 type=single &
 error_variable=.ACAR.dboxes.dbox_tem_har_cre.errorFlag
```

Figure 9. The ADAMS file of Agent transformation API.

encapsulation and other functions for developing the Agent based on the JADE specification, without attaching much importance to low-level implementation of the Agent. The Agents' operation monitoring and sequence diagram is shown in Figure 10.

The results and animation of bogie operation are generated through the simulation. The left lower curve in Figure 11 indicates the vertical damping force of the two-stage suspension on the third car bogie, and the lower right curve indicates the damping force in the horizontal direction of the two-stage suspension on the third car bogie. The simulation results verify the feasibility and effectiveness of the multi-Agent-based modeling and simulation method and related technologies in this project.

5. Conclusions

Based on the analysis of EMU models, this paper proposes a multi-Agent-based

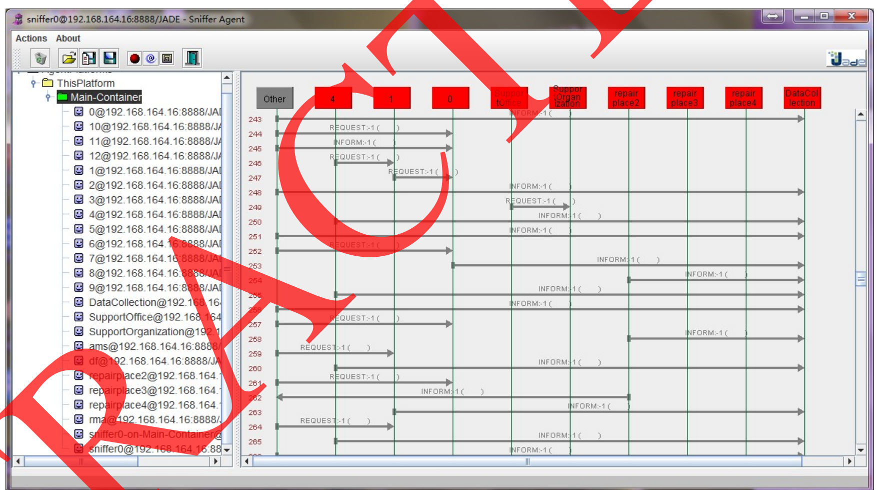

Figure 10. Agents management and message transmission sequence.

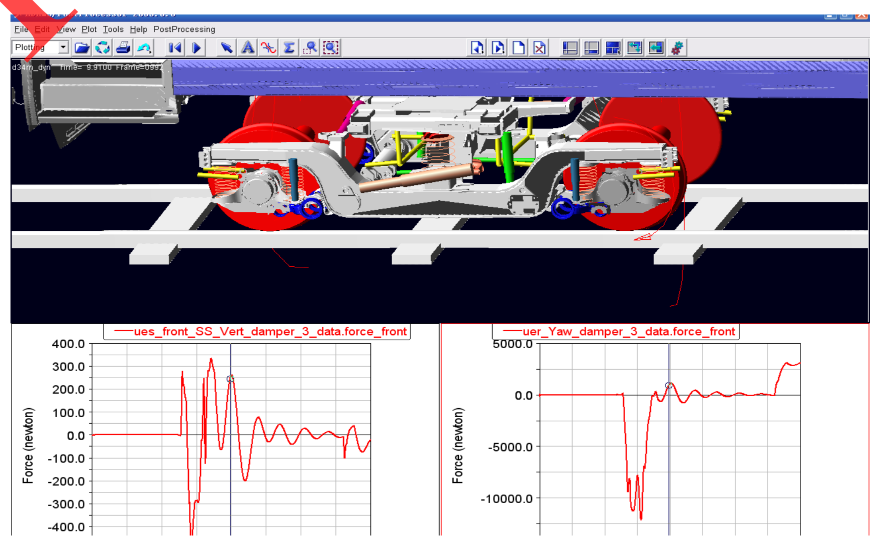

Figure 11. Bogie wheel derailment coefficient.

modeling and simulation method, designs a simulation framework and application process, constructs a simulation platform based on JADE, and develops a prototype system to verify and analyze the method.

Through the analysis of simulation result data, it is proved that the method of multi-Agent-based modeling and simulation is practicable. Every Agent in the prototype system works properly based on the preset properties and parameters. Especially, the simulation results are approximate to the actual EMU design parameters. The next step is to simulate more part based on multi-Agent to further verify the stability and robustness of the modeling and simulation platform in the distributed environment.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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