An AI based High-speed Railway Automatic Train Operation System Analysis and Design

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***Abstract*—Recent years, the research and application of High-Speed Railway（HSR） automatic train operation (ATO) system are under fast development, while the safety, energy efficiency and passenger comfort of ATO systems still need improvement. On the other hand, Artificial Intelligence (AI) technology, for example, Deep Learning, has been widely applied in automata industry such as robot control and driverless vehicle. In this paper, we propose a new idea of improving train control system performance with AI technologies such as Deep Reinforcement Learning and Imitation learning, and describe the system objective, structure and development process. The details of key processes such as establishment of Train Running Condition Evaluation Index, acquisition and processing of relevant big data, construction of AI based automatic train operation model and the program of simulation and experiment are presented in this paper, which provides a brand new and practical idea to the development of High-Speed Railway automatic train operation systems.**

Keywords—HSR, ATO, Artificial Intelligence, Deep Reinforcement Learning, Imitation Learning

I. INTRODUCTION

With fast society, economy and technology growth, High-Speed Railway (HSR) and metro, as the representative of the railway industry, are experiencing rapid development. In recent years, new technologies in railway industry are emerging, where Automatic Train Operation (ATO) is one of the most important research and application hot spot.

In metro systems, unmanned operation technology is under faster development due to the short line distance, low train speed, simple operation environment and less or none cross-line operation. By the end of April 2018, the Full Automatic Operation (FAO) has been applied in 63 metro lines in 42 cities around 19 countries and the operating mileage has reached 1003 kilometers. That is to say, there are about one quarter in all 157 cities with at least one subway line using FAO. Among those countries, China has huge potential since many FAO lines are under construction in multiple cities such as Beijing, Shanghai, Shenzhen, Guangzhou, Wuhan, Dongguan and Nanjing[1].

For HSR, Chinese Train Control System level 2 with Automatic Train Operation (CTCS2+ATO) has been applied in both Dongguan-Huizhou and Foshan-Zhaoqing intercity railway in the Pearl River Delta Intercity Railway Network. While Chinese Train Control System level 3 with Automatic Train Operation (CTCS3+ATO) is taking on track experiment in Beijing-Shenyang Passenger Line, and will start commercial operation in Beijing-Zhangjiakou intercity railway. As to international railways, relative researches have been carried out in traditional railway sectors. Société Nationale des Chemins de Fer FranCis (SNCF) declared its research plan to achieve Train a Grande Vitesse (TGV) unmanned operation by 2023[2]. The UK government also presented an investment plan with the amount of up to 450 million pounds, including the investment on next generation train with automatic operation which will significantly improves the railway transportation efficiency [3].

However, current automatic train operation technology is still based on traditional automata theory. Firstly, objective profile is generated according to line conditions, speed limit and train conditions. Then the train is controlled by train control algorithm to follow the objective profile[4]. This kind of train control theory leads to problems in safety, passenger comfort and breaks the balance between efficiency and cost. The details are as follows.

1.In safety aspect, traditional automata theory excessively depends on the protection of wayside signaling equipment to achieve safety. And there is lack of active safety protection.

2.Traditional automata theory cannot simultaneously consider operation efficiency and energy consumption. The need in at least one aspect is ignored in traditional theory.

3.The passenger comfort has noticeable difference compared to human driver.

In order to solve the above problems, a lot of work have been done all around the world. Many research groups in Australia, Singapore, Korea, UK and China have conducted studies on theories and application of train control strategy. Howlett and his group first established the energy consumption model of trains and proposed the optimization strategies[5,6]. Researchers in Singapore[7], Korea[8], UK

Supported by the National Natural Science Foundation of China (Grant No. 61790575).

978-1-5386-7528-1/18/$31.00 ©2018 IEEE

[9], Spain[10] and France[11] have also conducted a series of works on energy efficient train operation and the validity of control strategies has been verified in parts of lines. Recent years in China, a lot of relevant researches have been done from various aspects, such as improving train operation safety[12] or efficiency[13], decreasing total energy cost[14] and ensuring precise train stopping[15].

As to control algorithm research, the studies on ATO control algorithm went through the process of “Classic Control - Parameter Adaptive Control - Intelligent Control - Integrated Intelligent Control”[16], where PID control, fuzzy control and the ATO control algorithm which combines PID control and fuzzy control have been widely applied in engineering applications.

However, most of the above researches focus on the optimization of one aspect of operation profile or control algorithm. Moreover, most existing researches only aimed at local optimization on energy consumption, passenger comfort or precise train stop. Therefore, they are lack of global consideration based on the basic operation procedure using “Perception-Decision-Control” cycle.

According to the investigation, experienced driver would achieve better performance in the above train operation scenario compared with present automatic train operation system. This is because human drivers have broader perception method, more comprehensive decision and more sophisticated operation experience. Although there are relevant studies on the application of machine learning, such as neural network, on automatic train operation, most existing works focus on control algorithm or expert experience[17,18]. And few researches consider big data on operation condition, train condition and driver experience.

With the development of Artificial Intelligence (AI) algorithm and technology, for example deep learning, reinforcement learning and imitative learning, AI technology has been widely applied in traditional automata industry[19], and promising results such as biomimetic robot, unmanned aerial vehicle and driverless car have shown the huge protentional in application of AI and provided new idea for the development of automatic train operation technology.

In this paper, based on traditional train control theory, we use the latest AI technologies such as deep learning, reinforcement learning and imitative learning to propose a new artificial intelligence based automatic train operation technology proposal, in order to utilize the advantage of both intelligent driving and automatic driving, and to improve the global train operation performance considering safety, energy efficiency and passenger comfort.

II. AI-Based Automatic train operation System Analysis

A. System Analysis

As mentioned above, due to operation profile generation and train control scheme of traditional automata theory, as well as the lack of active perception of external environment, current ATO system has limits in safety, passenger comfort and balance between efficiency and cost. In this paper, we provide AI based automatic train operation system (short for iATO system) to solve the above problems in the following ways.

(1) The automatic train operation is a multi-objective and multi-phase decision problem. There are few quantitative analysis method to handle parameters such as passenger comfort and emergency management. In addition, sophisticated drivers have had strict training and gained a lot of driving experiences. These experiences contain basic operation principles and are difficult for quantification. Therefore, using imitation learning [20] to transfer experience of sophisticated drivers into data for the training of iATO model will help improve model initialization speed and the training efficiency.

(2) In order to solve the lack of perception of ATO, the proposed iATO system uses vast different types of operation related data as the basis of train control decision generation, and continuously optimizes the problem according to Train Running Condition Evaluation Index. Thus iATO uses Deep Reinforcement Learning (DRL) [21]which combines data mining ability of Deep Learning[22] and motivate decision ability of Reinforcement Learning[23].

The comparison of traditional ATO and iATO is shown in Table 1. The details of iATO model establishment and training is described in the following sections.

TABLE I. COMPARISON OF CURRENT ATO AND IATO

Indicators	**Current ATO**	***iATO***
Safety	Depend on Movement Authority from wayside equipment to ensure safe operation of trains.	Use perception techniques such as video and sensors to actively acquire line condition. Gain the ability to actively respond to emergency situations.
Energy Efficiency	According to operation schedule, speed profile is calculated to ensure the punctuality of arriving. Energy cost is not considered in calculation of speed profile.	Use energy cost as object to learn from train operation experience with deep reinforcement learning and generate energy efficient train operation profile.
Passenger Comfort	Frequent acceleration and braking due to PID based scheme, leading to poor passenger comfort compared with drivers.	Use imitation learning to learn from sophisticated driver and to improve passenger comfort.

B. System Design Principles

According to the theoretical and practical principles of train control system and machine learning theory, the iATO system proposed in this paper meets the following principles.

1. iATO system is compatible with current CTCS2 and CTCS3 train control system standard of HSR, and is able to adapt the requirement of centralized dispatching of HSR transportation.

2. iATO system operates under the supervision and protection of Automatic Train Protection (ATP) system to ensure the safety and reliability of train control systems.

3. In order to efficiently gain relevant knowledge from data, iATO uses offline training process in ground equipment before commercial operation and online self-learning process in onboard equipment during commercial operation.

III. AI BASED AUTOMATIC TRAIN OPERATION SYSTEM DESIGN

A. System Development Program

According to the design principles in Section II, the development and application procedure of iATO is shown in Fig.1.

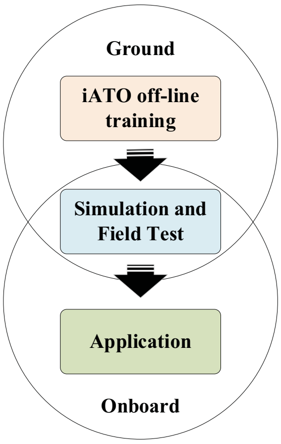


Fig. 1. Development Flow Diagram

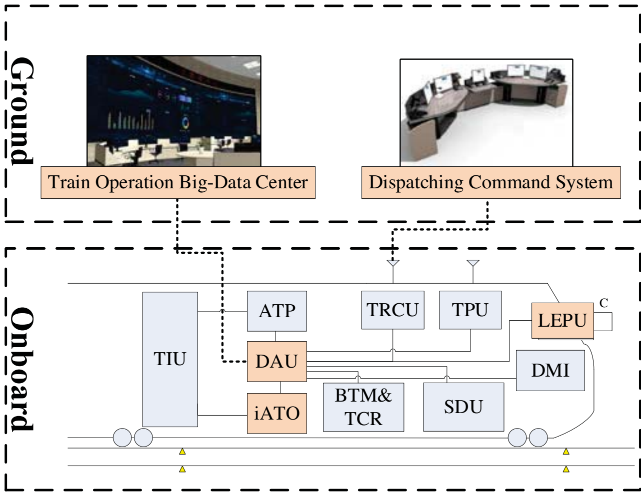
As shown in Fig.1, there are mainly 3 steps during the development of iATO system. (1) Choose the typical railway line, acquire train operation related big data information through all kinds of onboard sensors, and carry out training process of AI based train control model in iATO ground equipment. (2) Carry out tests and experiments about functionality, safety and stability of iATO system in lab and test line. (3) Employ iATO system in commercial operation line, and improve the train operation level of iATO system through self-learning method. The step (1) and (2) focus on training of fundamental and general train operation, and step (3) refers to continuous and independent self-learning of iATO system during commercial operation according to line condition, operation environment and transportation requirement of actual railway lines.

B. System Program Design

The system architecture of iATO is shown in Fig.2, iATO system mainly contains 2 parts, which are iATO onboard subsystem and iATO ground system. Compared with traditional train control systems, the additional equipment of iATO systems is shown in red color in Fig.2.

In iATO onboard subsystem, based on the relevant train operation information from DAU, AI based train control unit is in charge of the train operation under the supervision of ATP system. Traditional onboard equipment such as onboard ATP, DMI, TPU, SDU and LEPU are equipped in iATO subsystem which follow the current standard, and only development of interfaces with iATO subsystem is required. While new equipment need development to obtain more relevant information, such as Video Acquisition Unit, Driver Information Acquisition Unit, TRCU and so on.

In iATO ground subsystem, Train Operation Big Data Center is responsible for data record and process to analyze big data information and to support the training of iATO train control model as shown in Fig.3. While Dispatching Center is in charge of sending operation plan, temporary speed limitation, hazard warning and other information to trains.



- iATO - AI Automatic Train Protection
- DCU - Data Acquisition Unit
- TRCU - Train Radio Communication Unit
- TIU - Train Interface Unit
- TCR - Track Circuit Reader
- SDU - Speed & Distance Processing Unit
- ATP - Automatic Train Operation
- LEPU - Line Environment Perception Unit
- DMI - Driver Machine Interface
- TPU - Train Positioning Unit
- BTM - Balise Transmission Module

Fig. 2. System Structure

The functional structure and information flow diagram is shown in Fig 3.

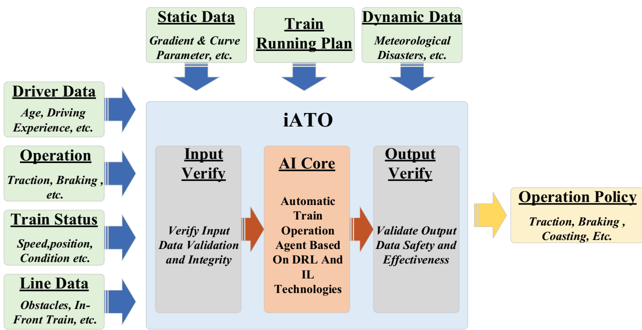


Fig. 3. System Function and Information Flow Diagram

As shown in Fig.3, firstly, a train operation condition evaluation system is built, and a general Train Running Condition Evaluation Index (TRCEI) is proposed based on multiple performance parameters, which takes safety, punctuality, passenger comfort, stopping accuracy and energy cost, etc into account. Then, the big data information system is built for the training process according to train operation relevant data acquired by sensors and further Processed as shown in Fig.4.

At last, a Deep Reinforcement Learning (DRL) based train control model is designed and trained using big data information system, in order to generate automatic train operation strategy according to decision basis.

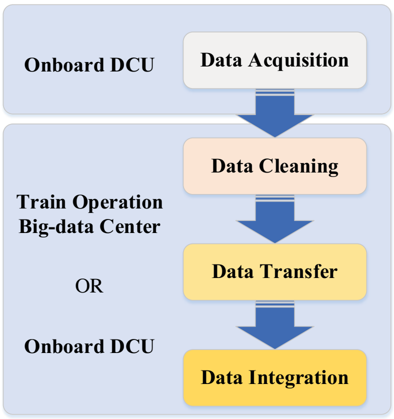


Fig. 4. Data Processing Flow Diagram

It should be noted that the train control unit in iATO system uses DRL based scheme. Generally, deep learning algorithm brings the so called Black Box problem, which means the conclusions are calculated using big data other than theoretical derivation. In order to solve the Black Box problem, a three-layer train control model is designed for iATO system, as shown in Fig.3. Two Check Unit is added before the input end and after the output end of Central Calculation Unit of the model, which guarantee the completeness and availability of perception information and the safety and continuity of control order to trains.

According to the above system design, details of train control model training are given in the following subsections.

C. Establishment and Training of AI-Based Train Control Model

The establishment and training process is the most important part of the iATO system. In this paper, we combine the advantage of deep reinforcement learning and imitation learning to establish a multi-layer and multi-input model for train control strategy generation. The model is shown in Fig.5.

Firstly, the deep learning model with basic train control strategy is established and trained using imitation learning method, with the acquired data of sophisticated driver's operation strategy as well as typical train operation environment and conditions such as line data, operation schedule and train speed.

Then, according to more of the acquired train operation environment data, such as cab video data, weather data and train condition, the DRL method (Deep Q-Network) is applied to improve the deep learning model. Based on the model in the first step, more complex train operation environment data is imported in to the model, and the reward calculated by TRCEI is given as the feedback of the model. At the same time, line data, train operation condition data and weather data are imported into the model using the same method. This is to help improve the model stability and reduce the uncertainty brought by driver's experience.

It should be noted that, because of the feature of AI technology, the iATO system is in fact an individual intelligent system which keeps learning from input data. Therefore, the design principles in this section only describe the early stage training process of iATO system. When iATO is put into commercial operation, an Incremental Learning method [24] is introduced to add new information to the trained model in order to improve the self-learning efficiency of iATO model.

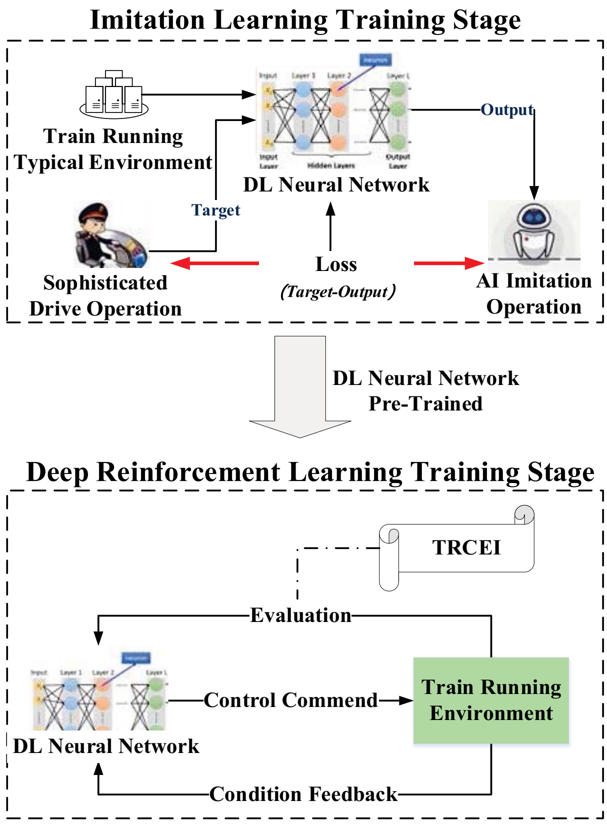


Fig. 5. Two Steps of Training Processes

IV. Test and Application Design

The test system structure is shown in Fig.6. After the early stage training process, the test and application process is carried out. In this process, the simulation and test platform in lab is established using hard-in-loop method.

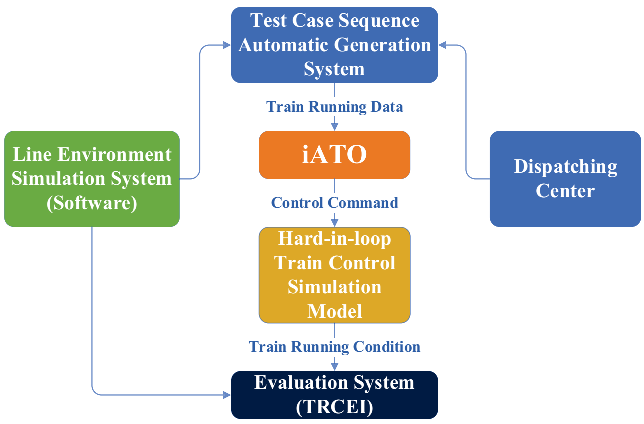


Fig. 6. Test System Structure

After the in-lab simulation and test process, a dedicated experimental line is chosen, and the actual operation of iATO-equipped train is used in the comprehensive experiment of iATO performance.

After the experimental line test, the trial operation of iATO in actual line will be implied in 2 steps, as shown in Fig.7.

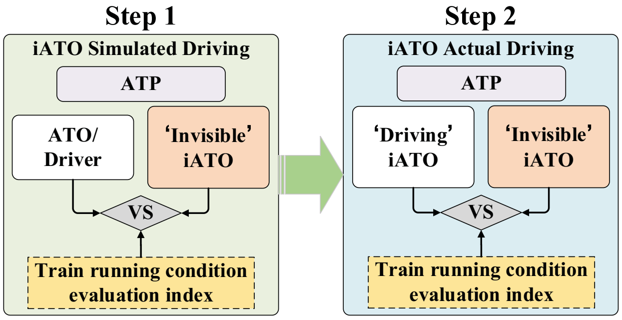


Fig. 7. Two Steps of Application Processes

Step 1, iATO system operates under the supervision of ATP in invisible mode. That is to say, according to the acquired data, iATO system generates control strategy but is not imported to the train. This control strategy is only used to compare with output of current ATO system or driver's operation using TRCEI as standard.

Step 2, after a certain amount of learning, when the general performance of iATO system calculated by TRCEI exceeds that of the current ATO system or the driver, iATO system will replace them. Then, iATO system is in charge of the train control and operation, and stops learning for the consideration of system stability. In order to continuously improve the performance of iATO system, in Step 2 we use an additional invisible iATO system to continuously learn based on the iATO system which is in control of the train. When the performance of additional invisible iATO system calculated by TRCEI exceeds current iATO system, an integration or upgrade process is implied according to the actual needs.

V. Conclusion and Future Work

In this paper, an new High-Speed Railway automatic train operation strategy based on Deep Reinforcement Learning and Imitation Learning is proposed. In this strategy, a comprehensive Train Running Condition Evaluation Index is established, and the acquisition method of train operation related big data is present. Using the above index and data, the automatic train operation model is built based on DRL and IL with the ability of perception and decision, in order to further improve the train operation performance.

In consideration of the complexity of high-speed train operation and variability of train operation situation, it is a huge challenge to realize the proposed AI-based automatic train operation strategy. In the future, according to the system design program, we plan to carry out the system design, in-lab simulation and commercial line experiment in steps, in the hope of building a new high-speed automatic train operation system which is able for engineering applications.

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