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Review of Digital twin for intelligent transportation system

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***Abstract*—Digital Twin (DT) is attracting the research interest of the traffic community in the last few years due to improvement of intelligent traffic management through the simulation of the transportation system predicting potential problems and optimizing traffic operation, which is considered as one of the most effective solutions of current traffic problems. In this paper, we propose a new DT concept of traffic based on characteristics of DT and connotation of traffic. We have summarized the difference and relationship between traditional traffic simulation and DT. A three layers technical architecture was proposed, including data access layer, calculation and simulation layer and management and application layer. Besides, we have analyzed the key technologies of DT in construction of traffic scenario and future applications of traffic DT. Results show intelligent expressway, self-driving, ITS remain the main developing directions of DT for traffic; although data mining, cloud computing and other data processing technologies have made some progress, in the face of massive traffic data, data loading technology and information extraction technology still need to be strengthened.**

Keywords- Digital Twin; Intelligent Transportation System; Traffic simulation; Traffic management

I. INTRODUCTION

Traffic problem is one of the important issues related to national development and people's happiness. The existing traffic situation in China is characterized by serious traffic congestion, difficulty in driving and parking, and low level of public transportation service, which not only brings great inconvenience to travelers, but also is a difficult problem that has been troubling traffic managers[1]. The main problems are reflected in the current traffic management strategy, including discrete applications, single and fragmented methods of solving traffic problems, leading to difficulty in considering the integrity and coordination of urban traffic management systems[2]-[3].

To solve the above problems, applying information and communication technology, Intelligent Transportation System (ITS) was born, which pays more attention to the interconnection of traffic data and systems, emphasizes the quality and effect of the overall solution, and manages the urban transportation system comprehensively[4]-[5]. However, the existing ITS technologies still needs to be improved in terms of data in comprehensiveness, accuracy, real-time analysis and processing[6]. In addition, the development of autonomous driving has put forward higher requirements on the accuracy and real-time of traffic information.

The emergence and rapid development of DT[7]-[10] with real-time, closed loop and comprehensive is expected to provide new technical support and developmental direction for ITS. It is to further expand the functions and improve the performance of ITS and make up for its deficiencies in solving current traffic problems.

The earliest twin concept originated in the aerospace field in 1972[11]-[12]. NASA's Apollo program built two identical spacecraft. One was launched into space on a mission and the other was left to reflect the operating status during the mission. It could assist engineers in analyzing possible situations in space and suggest corresponding strategies. Both information transfer and data flow occurred between two real physical entities, which were physical twins.

Since the cost of manufacturing another identical product used for analysis in large manufacturing industries is very high. Therefore, Professor Grieves[13] proposed the initial idea of DT in 2003. The concept is to construct a digital model in virtual space and make it interactively map with physical entities to describe the operation trajectory of physical entities through whole life cycle, as shown in Figure.1[14]. However, due to the immature technologies of computer digitization at that time, this concept wasn't conducted in-depth research.

NASA first officially introduced the concept of DT in the Space flowchart in 2010[15]. The goal of DT is to enable comprehensive diagnostic and predictive flight systems in continued operations[16]. Later, NASA and the U.S. Air Force jointly presented a DT paradigm for future aircrafts and pointed

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out that DT was one of the key technologies driving the development of future aircrafts[17].

In 2011, the concept of Industry 4.0 was proposed[18]. The new generation of computer technologies such as Internet of Things (IoT), cloud computing and DT were taken as critical developmental direction, among which DT was applied to the analysis, optimization and modeling of products in the whole life cycle. Subsequently, companies such as General Electric and Siemens also vigorously promoted DT, making DT in industrial manufacturing gradually perfect and mature[19]-[20].

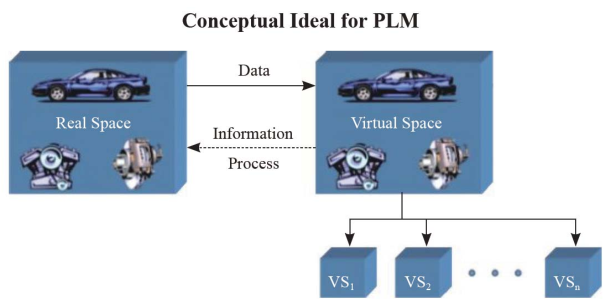

Figure 1. Grieves concept of digital twin[11]

With the development of technologies such as IoT, big data, artificial intelligence (AI) and machine learning (ML), DT has gradually penetrated into various fields of the transportation, such as urban traffic management, highways, intelligent vehicle infrastructure collaboration and autonomous driving.

Although major research institutions and related enterprises have launched their own DT concepts, researchers have made preliminary explorations on the construction of DT for transportation systems and have made some progress in data acquisition, visual processing, model construction, and numerical simulation[21]-[23]. However, it still lacks a precise definition, corresponding technical guidance in the field of transportation. The application of better instantiation has not yet been realized. In view of this, based on the current ITS, this paper systematically analyzes the correlation and similarities between ITS and DT, research key technologies of DT in the transportation field, and foresees its future development trend and direction.

II. DIGITAL TWIN OF TRANSPORTATION

A. Definition of Digital Twin in Transportation

The current widely accepted definition of DT is that technical means to digitally create virtual entities of physical entities to simulate, verify, predict, and control the whole life cycle process of physical entities with the help of historical data, real-time data, and algorithmic models[24]-[25], etc.

The above is a general concept of DT in the industrial manufacturing industry. The concept and definition of DT in the transportation field is still developing and evolving, which should have transportation connotation and be able to reflect the operational characteristics of the transportation system[26]-[27]. From the core meaning of DT and the development characteristics of transportation, DT of transportation can be regarded as a virtual world created in the digital virtual space after the digital abstraction of the real transportation system. Through the transportation model and data drive, DT forms a diversified virtual-real relationship with the real transportation system, which is very similar in the behavior and characteristics of the transportation elements, the evolution of the traffic temporality and state, and the development law of the transportation system. It enables real-time information interaction, closed-loop data flow, and adaptive iterative optimization between the real traffic system and DT. It has different twin degrees under different technologies and development periods of perception, virtual modeling, and data mining. It enables the study and control of the real traffic system through observation, analysis, deduction, and optimization of DT. It has the ability to actively, continuously, and in real-time perceive the state and update itself throughout the life cycle of the transportation system; the ability to accurately represent the temporality, state, operating laws, and evolution of the transportation system at any moment; the ability to discover knowledge, predict and deduce, and interact with the transportation system.

B. Similarities and differences between traffic simulation and digital twin

The field of transportation is no stranger to digital modeling techniques. Traffic simulation has long been one of the most effective means of studying traffic problems, with many mature software and techniques developed to date[28].

Simulation technologies are a modeling technology that applies simulation hardware and software to realize the solution of specific problems through simulation experiments with the help of numerical calculations and specific traffic scenarios and models built to reflect the processes of the traffic system[29]. The purpose of simulating the real traffic world by establishing a traffic model with deterministic operation laws and complete intrinsic mechanisms is to rely on the correct model, traffic data, and environmental data to reflect the operation laws, characteristics, and parameters of the traffic system[30].

DT can use real-time traffic data collected by sensing devices to build a virtual digital space mapping the real traffic system. Through simulation in the virtual digital space[31], it could analyze and optimize the simulation results, then feedback the optimization strategy to the real traffic system in real time, forming a complete real-time, closed-loop process.

Based on the above analysis, DT has many similarities with traditional traffic simulation both in terms of construction objectives and research contents. Both establish models through data and traffic theory to realize digital representation of real traffic systems in virtual space. Based on this, analysis, prediction, management and control of traffic systems can be realized.

The difference between traditional simulation and DT is that traditional simulation only relies on offline historical data to simulate the traffic system. It has a single traffic model and limited simulation scenarios, which cannot realize real-time, full life cycle supervision and data flow[32]. Comparing with the real traffic environment, the virtual simulation environment of traffic simulation is more simplified and isolated, with more information lost except for traffic elements. Little attention is paid to the virtualized expression of other elements besides the studied traffic objects. It is difficult for the single traffic model in the traffic simulation to reflect the operational characteristics and evolution laws of the traffic system and traffic elements that are variable and affect each other. It does not have the real-time and closed-loop characteristics of DT. In addition, DT also has optimization and analysis functions, and can also interact with real traffic systems in real time[33]-[34]. Traffic simulation can be regarded as the foundation and primary stage of DT, while DT can be regarded as the upgrade and final goal of traffic simulation. The differences between traffic simulation and DT are detailed in TABLE I.

Although the models built by DT in the virtual world are closer to the real traffic system than traditional traffic simulation, it is still difficult to twin the real traffic system, i.e., extent completely consistent. It is very difficult to express the dynamic traffic elements and the operation, evolution, and interaction laws between them only through models. With the development of perception technology, communication technology, data mining and processing technology, and modeling means, DT will be gradually closer to the road traffic system until become the complete twins.

TABLE I. COMPARISON OF THE CHARACTERISTICS OF DIGITAL TWIN AND TRAFFIC SIMULATION

Items	Transportation simulation	Digital twin
Features	Offline, Opened-Loop	Real-time, online, Closed-loop, whole life cycle
Functions	Reflecting the traffic operation pattern	Reactive traffic system operation rules, adaptive analysis optimization and feedback
Input data	Historical Data	Historical and online Data
Modeling	Traffic Theory and Models	Simulation, traffic theory and modeling, data fusion, knowledge graphs, etc.
Interaction	no	Real-time interaction and feedback

III. DIGITAL TWIN TECHNOLOGY ARCHITECTURE

The architecture of DT applied to transportation systems can be divided into three technical layers, namely data access layer, computational simulation layer and application management layer.

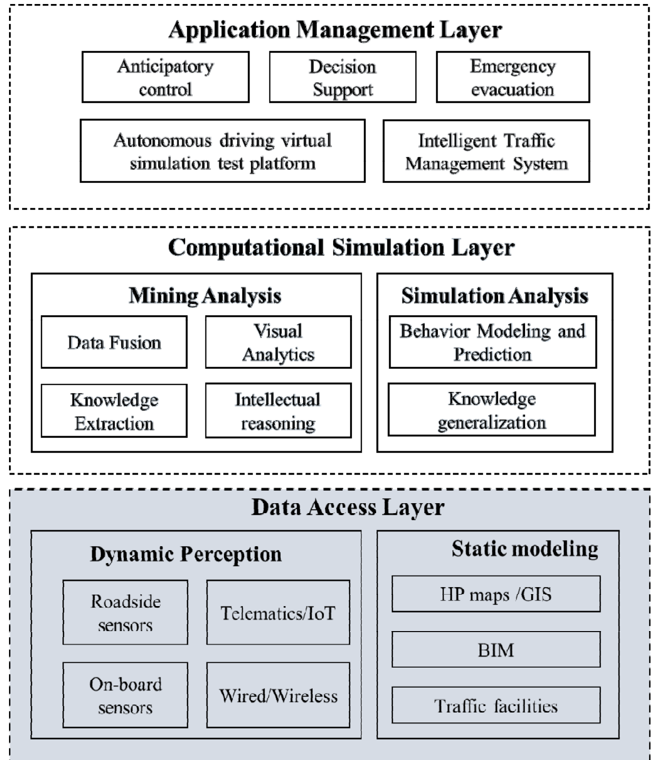

Figure 2. Technology architecture of digital twin

A. Data Access Layer

The data access layer realizes real-time comprehensive multi-objective, multi-level, multi-dimensional and multi-modal perception of traffic elements in the actual traffic system. It gives DT real-time and accurate data features reflecting the real environment state, mainly including static modeling of the traffic environment and perception of dynamic operating traffic elements.

Static modeling includes achieving accurate and comprehensive road feature characterization through HP map technology, while being able to meet real-time requirements and record specific details of driving behavior. It includes typical driving behavior, optimal acceleration and braking points, complexity of road conditions, and annotation of signal reception on different road sections[35]. Digital restoration of building facilities in outside road is achieved through Building Information Modeling (BIM). In addition, precise descriptions of various traffic facilities on the road, including signals, cameras, traffic signs and markings, etc., are also required.

Dynamic sensing is achieved through roadside sensors, vehicle sensors, wired/wireless communication, and vehicle network/IoT technologies and detection means to realize real-time, dynamic sensing of the overall operation of road traffic. It includes macroscopic and microscopic traffic information. Macroscopic information refers to road operation speed, density, flow, etc., traffic congestion status. Microscopic traffic information refers to specific details of pedestrian crossing, including the interaction behavior characteristics between pedestrians and vehicles, pedestrians, and non-motorized interaction behavior characteristics, crossing speed and other information. Microscopic information of vehicle including driving behavior details information, including acceleration and deceleration time, braking behavior, and response to different road facilities. These comprehensive and massive sensory data are transferred to the computational simulation layer to analyze the operation of the traffic system and to explore the operation laws of the traffic system.

B. *Computational Simulation Layer*

The computational simulation layer establishes DT model by collecting traffic data and establishing traffic models. It can discover the complex hierarchical relationships, interactions, and evolutionary processes among traffic elements in DT[36]. It generalizes the deep information and knowledge contained in it by using data mining technology and forms a multi-level knowledge model of DT to support simulation analysis.

Through virtual modeling technologies and real-time traffic data to achieve virtual restoration of the real traffic world, through visualization technology to truly reproduce the traffic system, and with forecasting capabilities to provide decision support for traffic managers and real-time personalized travel information for travelers.

C. *Application Management Layer*

The application layer presents diverse information such as DT, simulation calculation results and decision optimization models in a fusion for practical application. It needs and builds traffic management systems to control traffic facilities such as signals and electronic signage in real traffic systems in real time. Through phone APP, car network and other network communication methods, it sends alert information and control parameters directly to traffic participants, intelligent networked vehicles and self-driving vehicles to realize the global guidance control and decision optimization of the traffic system.

IV. Analysis Of Key Technologies For Building Digital Twins Of Intelligent Traffic Scenes

Using PD map, cloud computing, IoT, AI, big data, visualization, semanticization and other technologies to digitally replicate the real traffic system build DT traffic environment, fuse traffic real-time data. It could build a traffic information knowledge map, and display, mine, and analyze traffic spatio-temporal data to realize monitoring and warning, emergency handling, and congestion management, decision optimization and other functions.

The critical technologies for DT under the intelligent transportation scenario mainly include dynamic perception technology, virtual environment construction, data fusion and processing, and traffic element modeling technology, as shown in Figure 3. Among them, both dynamic perception technology, virtual modeling technology and data processing technology have mature algorithms and applications in the industry[37]-[39]. We will not elaborate on them here. The traffic element modeling is the most important part of the traffic digital twin system. It is one of the most difficult problems in the traffic field. Therefore, this paper introduces the traffic element modeling in detail to provide a reference for researchers in the traffic field.

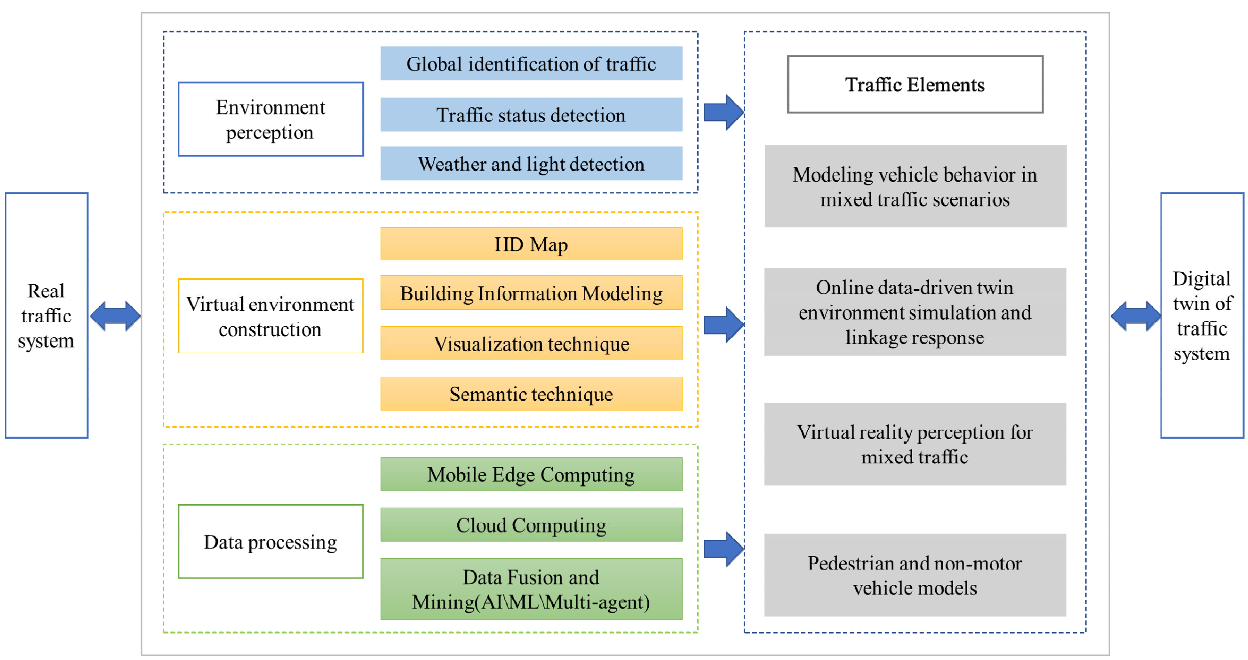

Figure 3. Key technologies of DT for intelligent traffic scenario

A. Modeling vehicle driving behavior in mixed traffic flow

The driving behavior model in the existing traffic simulation software cannot be used directly in the hybrid traffic simulation. It is difficult to meet the needs of the construction of hybrid traffic scenarios that meet the actual operating conditions. To analyze the behavior characteristics and simulation methods of different traffic elements in mixed traffic environment, including cars, buses, trucks, non-motorized vehicles, and pedestrians[40]. The road network construction method is established considering non-motorized vehicles and pedestrians' right of way, analyzing the inherent properties and borrowing patterns of different lanes, studying traffic signal timing and optimization analysis methods, reproducing real information timing in virtual scenarios, and supporting the simulation of dynamic adjustment based on traffic conditions.

B. Environment simulation of digital twin and linked response

Traffic scenes include online weather data, signals, electronic guide signs, video monitoring data, facility inspection data, equipment status monitoring and other multi-source sensor data. The existing DT fails to consider the impact of online sensing data on the construction of "human-vehicle-road-environment". The sensor data is disconnected from the construction of environment and operation simulation. It is difficult to reflect the real state of traffic operation scenes. Analyzing the characteristics of multi-source sensor data in traffic scenes and the relationship with virtual environment construction, it can realize the display of sensor data in virtual scenes and the setting of environmental elements[41]. based on online meteorological, climate and sunshine data, integrating real-time and historical data from urban spatial video images and multi-sensors, environmental simulation technology is proposed to realize the simulation of environmental change conditions and spatial sunshine distribution under different conditions. The impact of online data changes on the four elements of "people-vehicle-road-environment" is analyzed to realize a more realistic virtual traffic environment through continuous iterations of online data fusion, environment construction, and linkage response.

C. Virtual Reality perception of mixed traffic

Most of the existing traffic simulation results are displayed by data output, screen display and graph visualization. There is a lack of experimental methods that can be intuitively perceived and fed back online[42]. The perceptual characteristics and feedback need of different traffic participants is analyzed to build a hybrid traffic perception experiment to meet the needs of multiple people in the same scenario, which is conducive to the realization of cooperative perception and human-oriented feedback evaluation of multiple traffic participants in hybrid traffic. Virtual driving, virtual riding, and virtual walking systems are used to build a mixed traffic perception environment with multiple participants. In the same mixed traffic scene, there are six types of participants: drivers, cyclists, pedestrians, bus drivers, and bus passengers. Different participants observe the same scene from different perspectives and in different ways, providing each type of participant with scene perception and evaluation feedback means that meet their role calibrations. Through the same scene calibration and collaborative interaction of multiple traffic participants, virtual driving vehicles, bus vehicles, bicycles and pedestrians are identified and positioned in the same scene, realizing the operation simulation and virtual reality perception of multiple traffic participants in the same road environment, supporting data collection, analysis and experiments related to the behavior and psychology of traffic participants under normal and emergency conditions.

D. Technologies to be studied

With the rapid development of the IoT, AI, ML, traffic big data and other technologies, DT has shown good prospects in the field of intelligent transportation, gradually gaining the attention of major enterprises and research institutions. The industry has gradually begun to focus on and explore the technical system, critical technologies and application potential of DT[43]-[45]. However, there is still a huge gap between the promising prospect depicted by DT and the realistic level in the field of intelligent transportation. Many technical requirements are still not available, and there are still many issues to be studied, specifically in the following aspects.

- Virtual-real interaction technology

Conceptually DT can realize the function of information intercommunication, data interoperability and real-time interaction between real traffic system and virtual twins. But in practical application, DT still stays in offline digital simulation of traffic system, and there is no breakthrough in real-time interaction and online closed loop between virtual world and traffic system. Therefore, the study of real-time virtual reality interaction technology for DT in traffic scenes is one of the urgent problems to be solved in the future.

- Multi-traffic elements interaction model in mixed scenarios

The interaction model between traffic elements has always been important research content in the field of transportation. How to establish real-time multi-scene and multi-elements interaction models of human, non-motorized vehicles, and vehicles through perceptual data, so as to be able to more realistically reflect the micro-operation process of complex traffic systems and thus ensure the fidelity of the interaction process of traffic individuals and traffic individuals, is one of the future research directions.

- Efficient data processing technology

Although data mining, cloud computing and other data processing technologies have made some progress, the data loading technology and information extraction technology still need to be strengthened in the face of massive traffic data. Taking autonomous driving technology as an example, it will generate tens of thousands of data per minute, which will soon reach its storage limit, severely limiting the development of autonomous driving test.

The current DT involves main technologies such as logo perception, edge computing, full-element expression, simulation and so on. The massive data processing technology, cloud-edge-end computing synergy technology and traffic modeling technology also need to be improved.

V. DT Application in Transportation

The typical applications of the traffic DT include the virtual simulation test platform for autonomous driving, the intelligent traffic simulation projection platform, the intelligent highway management platform and the intelligent traffic control system.

A. Autonomous driving virtual simulation test platform

Autonomous driving is one of the most typical applications of DT[46]. DT combines traffic data, weather data and environmental data collected by sensing devices with HD maps to realistically restore the real world into a digital scene, enabling high precision simulation of roads, terrain, traffic signs, light, weather, traffic flow[47]-[49], etc. Using a highly realistic and scenario-rich simulation platform to test and train autonomous vehicles based on real road data, intelligent model data and case scenario data can improve the decision execution and safety stability of intelligent driving and accelerate the promotion and popularization of safer landing of driverless vehicles.

B. Intelligent Traffic Simulation Platform

Based on DT, the intelligent traffic simulation extrapolation platform is used to modify the signal lights, road measurement equipment and other related information parameters through the traffic data in the extrapolation platform test. Decision-making program feedback to reality to guidance of traffic operations. Traffic simulation platform is used to construct traffic simulation scenarios to provide real-time trajectory, and real-time response to the feedback of the communication simulation. The simulation results are used for dynamic traffic flow control program comparison, road signal control, intelligent guidance, route planning, chokepoint control diversion, late road flow prediction and other congestion control services and management[50].

C. Intelligent Traffic Management System

Urban traffic is a main management scenario for traffic managers. Intersections are also one of the most densely arranged scenarios for traffic sensors[51]. Intersection-centered intelligent traffic control systems are one of the popular typical applications of DT. Through DT to build urban network model, according to the actual application needs for simulation, automatic calculation of urban road network density, arterial network density and other content are calculated. It can realize that operation analysis of road work and automatically optimizing the solution are solved at the meantime to achieve full control of urban traffic.

D. Intelligent Highway Management System

Smart highway management system is also one of the hot spots of DT construction and application. The current highway intelligence construction mainly focuses on the highway entrance/exit, non-stop toll collection, inspection, road surface disease detection and all-weather access system. Among them, the all-day access system is one of the important applications of the current smart highway construction based on digital twin technology.

The data information detected by vehicles and road sensors is collected in real time and processed by digital twin technology, combined with lane level high precision maps to present the final effect in real time on the car-end display, assisting drivers to understand the road conditions and surrounding vehicle operation of the vehicle, thus ensuring the normal passage of vehicles[52]-[53]. The information of the road the vehicle has traveled will also be uploaded to the digital twin visualization platform synchronously to help traffic managers make early warning judgments on the road passage environment.

VI. Conclution

Driven by the combination of technological evolution and demand upgrade, DT technology provides new concepts, new ways, and new ideas for intelligent traffic development. Through the organic coupling of advanced technologies in multiple fields such as intelligent perception, network communication, artificial intelligence, and intelligent control, it can crack the technical bottlenecks faced by the construction of intelligent traffic management system nowadays. With the continuous development of related technologies and interdisciplinary cross-fertilization, DT for ITS will continue to develop and eventually form a complete technical operation system through virtual service reality and data-driven governance.

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