CPSS Models and Spatiotemporal Collaborative Optimization of Urban Public Transport Dynamic Network

Gang Xiong, *Senior Member, IEEE*, Bin Hu, Xisong Dong (Correspondence Author), *Member, IEEE*, Fenghua Zhu, *Member, IEEE,* Zhen Shen, *Member, IEEE,* Xipeng Zhang

Abstract—**With the increasing popularity of urban bus cards and smart phones, it becomes necessary and possible for the real-time collection of public transport status to analyze passengers' OD, passengers' travel dynamics, bus network's status and dynamics. In this paper, the framework of Cyber-Physical -Social-System (CPSS) models of Urban Public Transport Dynamic Network (UPTDN) is presented to achieve passengers and buses' adaptive and collaborative optimization. Its main contents, research schemes, and computation experiment and analysis evaluation are presented in this paper. This system can achieve such functions as information acquisition, collaborative and personalized service for every passenger and bus, and can continuously improve the passenger service and buses scheduling's quality by pursing their adaptive and collaborative optimization.**

I. Introduction

Urban public transport is the main means to meet the increasing travel demand of urban residents and to reduce traffic jam and pollution [1,2]. However, the increasing trend of the share ratio of public transport among urban transports is not obvious. On the one hand, it is due to the rapid increase of urban private cars, on the other hand, there are still many problems exist in urban public transport, such as insufficient transparency and sharing among traffic information, inconvenient transport transferring of different kinds of public transport modes, and so on. These disadvantages reduce the passengers' choice of urban bus traveling.

Along with the popularity of smart phones and vehicle terminals supported by mobile Internet, GPS/Beidou navigation, sensing modules (cameras, acceleration sensors, gravity sensors, etc.), a variety of networks (2/3/4G, WiFi, Bluetooth) and Mobile Social Network (MSN) are added such functions as location awareness, asynchronous interaction, crawling and labeling, automatic data processing. For example: the global real-time taxi software "UBER" is now covering 344 cities from 63 countries around the world; in China, the intelligent real-time taxi APP "DiDi" (www.xiaojukeji.com) can achieve self-organizational optimization of passengers and taxis in the time and space; in the bus system, the real-time bus APP like "CheLaiLe" (www.chelaile.net.cn) has been able to provide real-time bus information in most Chinese big cities. These applications have been fully proven that MSN can support a variety of traffic information service platform, and greatly improve the efficiency of "passengers searching for public vehicle like bus/taxi, and public vehicles searching for passengers".

In line with the development trend and demand of urban public transport, this paper takes the urban public transport with fixed roads and vehicles as the main research object. It mainly studies: how to build Cyber-Physical-Social-System (CPSS) model of Urban Public Transport Dynamic Network (UPTDN) involving roads, vehicles, passengers and environment with the help of mobile IoT and big data? how to measure the road and vehicle's status, like every bus's travel data? how to provide large-scale transport monitoring and optimization tools? how to seek for their self-organization collaborative optimization method in spatiotemporal domain? how to provide intelligent & personalized information services for urban public transport to improve the urban public transport share ratio? and how to promote the green low-carbon development of urban transport?

The organization of the paper is as follows: Section II gives a comprehensive introduction of research status and development of urban public transport, CPS (Cyber Physical System) &CPSS and CPSS-related transport field. The main contents of CPSS model of UPTDN and its research schemes are proposed in Section III and Section IV, respectively. Finally, the conclusions are drawn out in Section IV.

II. Research Status and Development

A. The Application and Research Status of Urban Public Transport

American's urban transport facilities, service facilities and management tools are more advanced than most countries. The TRAVET consists of transport management center, information and service center, and vehicles equipped with navigation devices, to provide such functions as real-time route guidance with the useful information service system. The transport administration of more than 25 states in US can provide an efficient and effective real-time traffic information services to improve every traveler's efficiency and security, based on big data technology. According to the report from

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G. Xiong is with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China. (e-mail: gang.xiong@ia.ac.cn).

B. Hu is with the Cloud Computing Center, Chinese Academy of Sciences, Dongguan, 523808, China. (e-mail: binhu@ia.ac.cn).

X. Dong is with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China. (corresponding author to provide e-mail: xisong.dong@ia.ac.cn).

F. Zhu is with the Beijing Engineering Research Center of Intelligent Systems and Technology, Institute of Automation, Chinese Academy of Sciences, Beijing, 100190, China. (e-mail: zhufh@casc.ac.cn)

Z. Shen is with the Qingdao Academy of Intelligent Industries, Qingdao, 266109, China. (e-mail: shenzhen@casc.ac.cn)

X. Zhang is with the School of Computer and Control Engineering, University of Chinese Academy of Sciences, Beijing, 100049, China. (e-mail: xipeng.zhang@ia.ac.cn)

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American Public Transport Association (APTA), public transport can save $10,000 per US passenger compared to private cars, while in New York and other big cities even more can be saved.

The representative traffic information systems in EU include SOCRATES, EURO SCOUT, TransportMaster, RDS-TMC, and so on. In order to realize the strategic goals of the zero-emission of carbon dioxide in major EU cities in 2030, and giving up traditional fuel vehicles in 2050, the EU's HORIZON 2020 project focused on smart green integration and energy conservation in 2014-2015, and give fund to support European VI bus which can reduce emission and save energy about 30%. In 2016-2017, EU proposed CIVITAS 2020 research program and launched a series of science and technology projects, which can research and develop resource-saving city transport system to meet the socio-economic and urban sustainable development needs and technological trends.

Japan's representative traffic information system is the Vehicle Information Communication System (VICS), which is the processing and distribution center of road traffic information, including information collection, processing and editing, sharing and application. VICS can timely edit, process, and transmit transport congestion, driving time, transport accidents, road construction, speed and route restrictions and parking spaces and other information from police departments and highway management departments to every driver and passenger, especially display traffic information in text and graphics onboard.

In China, about 600 - 800 cities are constructing “smart city” or related projects, and among them public transport is an important part. But, there is a certain gap between the development of urban public transport and the rapid development’s requirements of urban economy and society, and the continuous improvement of the urban residents’ living standards. There still exist prominent problems, such as the insufficient construction of public transport infrastructure, the low transport supply capacity, and the low transport efficiency and quality of service (QoS). The travel sharing ratio of the public traffic in China's large cities are only about 20% on average, and sharing ratio of the public traffic in small and medium-sized city are less than 10%, and the average speed of most urban public transport is becoming lower and lower, and the long waiting time, low punctuality rate, uncomfortable and inconvenient ridding, and other serious issues directly affect the competitiveness and attractiveness of the buses compared with other transport modes.

In the field of urban public transport research, Aslam *et al.* [3] researched and developed taxi congestion bypass program and system based on real-time perception of the road congestion situation, and the simulation results of more than 1,000 vehicles show that the travel time can be reduced by about 15%. Lin *et al.* [4] studied the classification characteristics of bus passenger trips based on those historical data from the bus passenger management system. Nakamura *et al.* [5] studied the personalized public transport service system, which can recommend bus travel path for each passenger dynamically according to the relevant buses operation status, the passenger’ travel demand and historical record. Kokkinogenis *et al.* [6] studied the establishment of artificial transportation system considering the social factors and policy elements, and analyzed and validated the rationality and effectiveness of the various transport policies on the traveler’s behavior through experiments on various systems. Chen *et al.* [7] studied the interactive and personalized traveler's path planning approach. IEEE Trans. ITS organized a special discussion on “ITS with Complete Transport Control” in 2014 [8]. Nunes [9] predicted the data of passengers’ getting off based on the information of each passenger’s getting on the bus (time, line, station name, payment amount) from bus ticket system. Lam *et al.* [10] proposed a combination of auctions through linear integer programming and automatic bus service operators to provide cost-effective and market-oriented bus services for travelers.

B. *The Research Status of CPS&CPSS*

In 2007, Cyber-Physical System (CPS) is proposed in US, which is a complex system consisting mainly of engineering complexity, and is becoming a hot topic all over the world [11]. The United States have applied CPS for transportation, defense, energy, medicine, agriculture and large construction facilities, etc. IBM puts forward that CPS is a strategic application concept practice of "Smart Earth". The National Science Foundation (NSF) in US have funded more than 500 research projects on CPS’s basic theory, method tools, platform systems, etc.

However, the existing research on complex systems focuses on one aspect of its engineering complexity or its social complexity. In complex systems, people are often designers, builders, operators and end users. Then, people and other social complexity elements cannot be ignored or even become decisive important role in the complex system. Therefore, to achieve secure reliability and efficient management of complex systems, the engineering complexity elements and social complexity elements must be studied equally as an integral whole. To this end, Cyber-Physical -Social Systems (CPSS) is proposed [12].

CPSS is a kind of general complex system composed of Physical System, related Social System, Cyber system which connects the above two systems (Fig. 1). It can realize the connection of Physical system and Cyber system through sensor network, and the connection of Social system and Cyber system through social sensor network, so that the physical + social system can "map" equivalently to the Cyber system [13]. On this basis, through mutual understanding, the actual situation of interaction, and together improvement of three systems in CPSS, safe and efficient operation of CPSS and other management and application goals can be achieved step by step [14].

Based on CPS, CPSS adds human and social factors into the management and control range of complex system [15]. CPSS extends the scope of research to the social network system. It is an organic combination of human organization and physical entity system through intelligent human -computer interaction, which is the basis of intelligent management of complex system [16, 17].

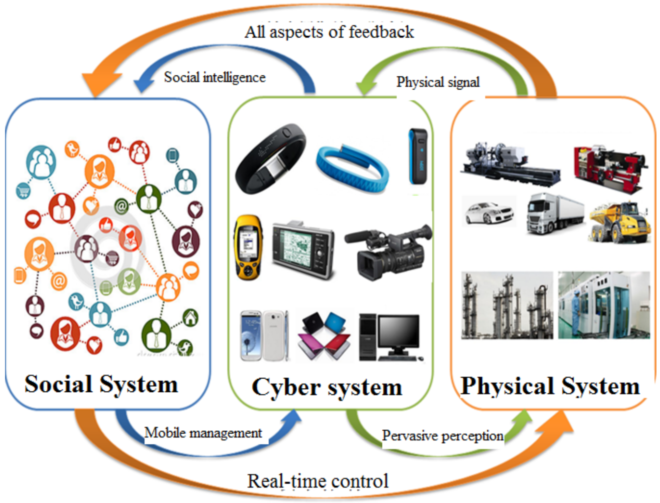

Fig. 1. The framework of CPSS

C. The Research Status of CPSS-related Transport

In the field of CPSS for transport, Sarah [18] provided users with personalized continuous optimization of traffic information services. Figueiras *et al.* [19] developed a personalized and interactive transport service mobile APP based on Knowledge Base funded by EU FP7 MobiS project. Machado *et al.* [20] merged social networks into mobile APPs in public transport, aiming to improve bus passenger satisfaction and reduce travel time. IEEE Trans. ITS organized a special discussion on "Real-Time Social Transportation with Online Social Signals" in 2014 [21]. Mitrea *et al.* [22] changed the city buses into a traveler's social places through the mobile APP value-added services. Pereira et al [23] researched how to extract transport anomalies to predict the flow law through the transport card data, mobile operator data, social media and related transport events and transport hotspots. Ning *et al.* [24] studied mobile-based localization algorithms and transport pattern classification algorithms. Cui *et al.* [25] studied the method of extracting traffic information from the textual data of social media. IEEE Trans. ITS organized special discussion on "Computational Transportation and Transportation 5.0" [26] and "Transportation Games for Social Transportation" [27], respectively in 2014. Guo *et al.* [28] studied the perception, communication, computing, control and application in CPS-ITS. Fu *et al.* [29] proposed an iterative search algorithm based on the relevant rules to extract information such as transport events from social media data to achieve transport monitoring. Zheng *et al.* [30] discussed the acquisition, cleaning and fusion techniques of various big data, and the integration, extraction and application of real-time transport conditions based on natural language and text. Dong *et al.* [31] proposed a framework of future innovative urban transport. Xiong, *et al.* [32] presented novel ITS based on space-air-ground big-data. He *et al.* [33] proposed to use mobile data, bus cards and other social signals to collect transport demand, forecast transport congestion and find congestion reason, to release the shortest or fastest transport path and other induction information. Dong *et al.* [34] proposed a parallel transportation management and control system for bus rapid transit. Xiong *et al.* [35] presented parallel transportation management and control system for subways. Li *et al.* [36] proposed traffic signal timing via deep learning. Wang *et al.* [37] proposed a review in crowdsourcing in ITS. Li *et al.* [38] presented a new framework of parallel learning based on deep learning approach. Lv *et al.* [39] reviewed the social media based transportation research. Dong *et al.* [40] proposed a new real-time scheduling strategy based on viedos. It can be seen that CPSS transport is the forefront of theoretical research and the forefront of urban public transport application.

III. Main Contents

Urban public transport is a typical representative of CPSS. It also involves engineering complexity and social complexity. It is characterized by dynamics, openness, interaction and automation. Based on CPSS model of urban public transport dynamic network (UPTDN), human and vehicle behavior can be analyzed, simulated and verified, to aim to the collaborative optimization of all elements existing in the service, scheduling & control level, and different time and space domain. Figure 2 depicts the main components of CPSS model of UPDTN. The main research contents are summarized as follows.

A. Basic modes of UPTDN

- The collection and analysis of bus data

Ordinary bus data includes static data and dynamic data. The static transport data mainly includes the basic information of urban transport road network and other facilities. Dynamic transport data includes the data of residents' travel behavior and traveling data, the collected vehicle information, real time vehicle location data, bus operating data, and so on.

- The collection and analysis of bus information based on social network

It is to study the collection technology of traffic information in social network based on text analysis and machine learning method, and to analyze transport flow, transport speed and travel time of the traffic information obtained from social media in combination with the data obtained from transport detectors in physical world, and to study transport event detection and interaction under the combination of the Cyber and physical spatial data, and to analyze the temporal and spatial characteristics of urban traffic information, finally to analyze, diagnose and reason the urban transport scene.

B. The Construction of CPSS Model of UPTDN

CPSS model of UPTDN can be built up to study complex urban public transport system. It is to construct a self-perfect system, which embodies the whole transport characteristics. It includes: data collection and aggregation of urban public transport based on physical and social sensor network; the behavioral model and the verification of passengers, drivers, and vehicles in urban public transport; the multi-scale and mixed complex dynamic network model and verification of CPSS; the design, analysis and verification of CPSS system; the construction and verification of artificial system and knowledge automation system; the relevant technology such as cloud computing and big data. It can be used to study the basic dynamic laws of individual vehicles or transport behaviors to study the various operating conditions of the transport system and the urban development, and the influences and other social activities on the interaction of the emergences of transport phenomena, to reveal the operation of the transport system and the inherent characteristics.

C. Analysis of Human and Car Behavior Laws based on CPSS Model of UPDTN

It is to study the computational experiment method based on CPSS model of UPTDN, and predict and analyze the behavior of urban public transport system based on various transport scenarios where various kinds of tests can be carried out. The algorithm in actual transportation system is applied to the system in the form of modules and components, including various learning strategies and optimization algorithms, qualitative and quantitative calculation of evaluation algorithm and transport scenes, to provide specific algorithm modules that will dynamically analyze, evaluate and optimize the course and results of public transport calculation, and update the evaluation results in conjunction with the evaluation index system. It mainly includes: the design methods of computation experimental; the computation experiments and their results analysis of the evolution laws of vehicle behavior, personnel behavior, and personnel and vehicle hybrid behavior; and the analysis and evaluation of variable regulation plans.

D. Typical Application of CPSS Model of UPDTN

Based on CPSS model of UPTDN model, a variety of application research can be carried out:

(1) Evaluation and optimization of traffic lights control scheme for urban public transport network. The actual transport data is used to construct the transport flow control system and the transport evaluation index system. Then, the transport signal control scheme is evaluated based on the results of computation experiments considering pedestrian crossing, driver's driving behavior and other social factors constraints, and the optimization suggestions are given.

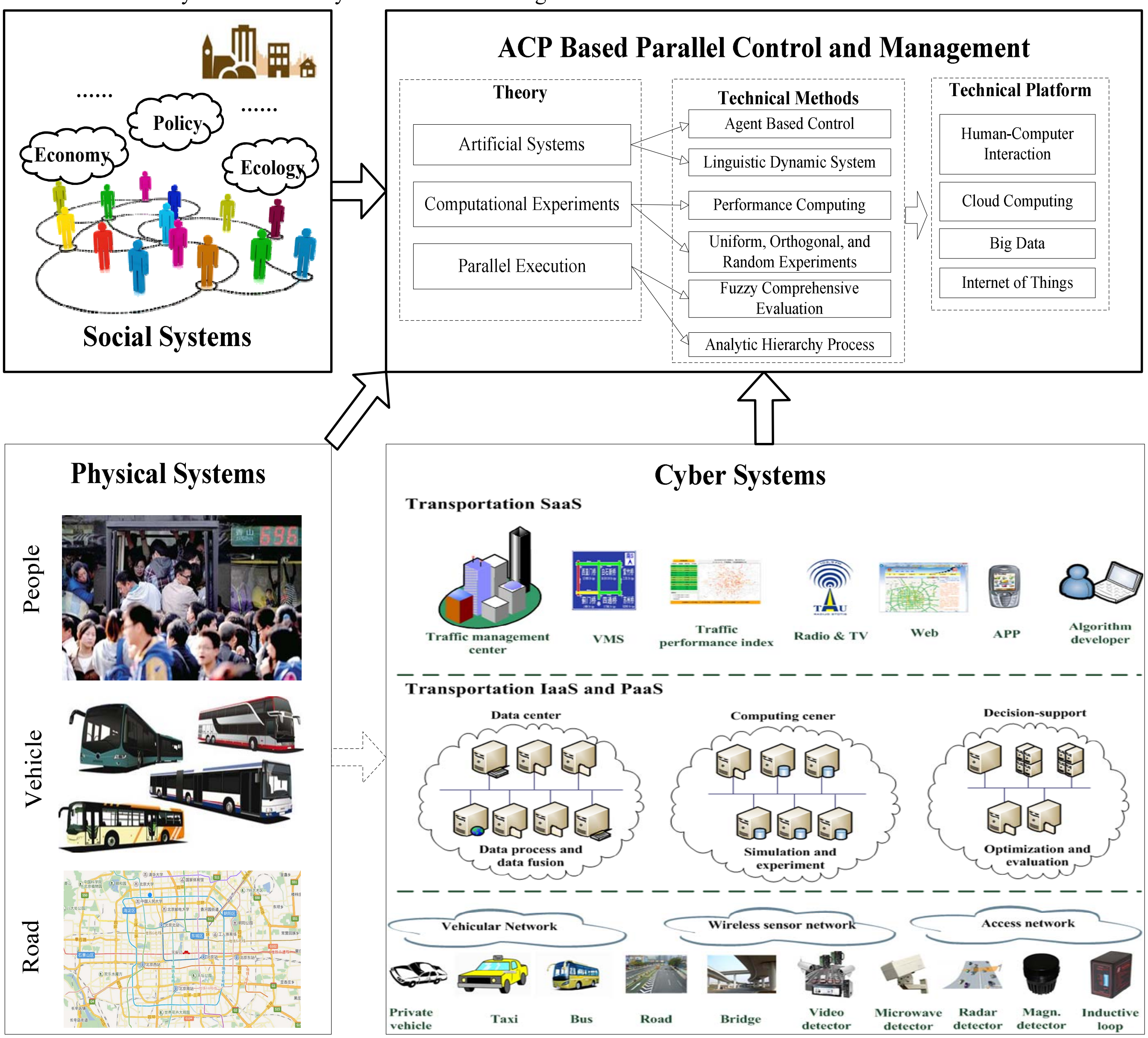

Fig. 2 The main components of CPSS model of UPTDN

(2) The human and vehicle behavior regulation. The regulation of urban public transport vehicle behavior; the regulation of urban bus passenger travel behavior; urban public transport personnel and vehicle mixed behavior regulation; UPTDN's space-time domain matching degree definition and dynamic analysis.

(3) The collaborative optimization of space-time domain of urban transport, such as the collection, interaction, service and induction of bus passengers and vehicles personalized traffic information.

IV. Research Schemes

A. Data Collection of Urban Public Transport

Urban transport data includes static data and dynamic data. The static transport data mainly includes the basic information of urban transport road network (road grade, length, charge information), road information of public transportation (line, ticketing, station, transfer point, etc.), parking lot information (parking location, name, total number, open and close, idle berth, etc.), and so on. Dynamic transport data sources are widely distributed in various forms, including passengers, cars, roads, driving behavior, paid behavior, travel behavior, vehicle information, real time vehicle location, bus operating, taxi operating, road transport volume, average speed, congestion status, etc.

B. Urban Public Traffic Information Collection and Analysis Based on Mobile Social Network

The traffic information collection platform can be constructed. On this basis, the traffic information from MSN and its classification can be extracted with on text analysis and machine learning methods. The traffic information includes transport events, transport congestion information, transport accidents, road construction, road control, transport weather, transport public opinion, and so on.

Based on the information fusion and cross validation of traffic information obtained from MSN and the transport detectors, the transport flow, speed and travel time can be forecasted using deep learning, probability map and other statistical methods. Also, the transport event detection and the urban traffic information spatiotemporal characteristics can be achieved by using the in-depth analyze, diagnose and reason of urban transport scenarios.

C. Data Processing of Urban Public Transport

Through more diversified data fusion, intelligent analysis can be achieved to provide more powerful data support. It can preprocess, store, manage, mine, predict, and analyze the selected data.

The traffic data of public transportation system are widely distributed and diversified. The main data sources are people, vehicles and roads, which need to be fused before analysis. Multi-source traffic information fusion is divided into three levels: the basic level is the data-level integration, which only completes the data preprocessing and simple association; the second level is feature level fusion, which is based on the characteristics of existing data to predict transport parameters; the third is state level fusion, which can determine the transport state according to the current transport flow information. The basic process of transport flow information fusion includes multi-source information extraction, information preprocessing, fusion processing and target parameter acquisition and state estimation.

D. Data Prediction of Urban Public Transport

The forecasting model is divided into three levels: basic data layer, characteristic attribute layer and state description layer. The basic data layer can be used to predict the transport flow data. The attribute layer is used to predict the transport flow characteristics, the transport event and type, the road congestion. The state description layer is to make the network service level evaluation, the development forecast and the event impact assessment. In the aspect of public transportation, it can forecast the changing rules of passenger flow and future development trends, to obtain the target passenger flow, to analyze the distribution of passenger flow of a certain line, and to analyze the route adjustment and the impact of the relevant lines, to predict how the passenger distribution, to give an intuitive analysis of the conclusions, and to provide supportive decision support for the reasonable adjustment of public transport network.

E. Computation Experiment and Analysis Evaluation Based on CPSS Model of UPTDN

Based on CPSS model of UPTDN, its intelligent, automated and unified computing platform can be built up to complete the task analysis and evaluation. The assessment objective is vehicle's spatiotemporal saturation and evacuation time. Input parameters include the number of passenger and vehicles, route, evacuation conditions, traffic environments, and so on. According to the input information of public transport vehicle's dispatching program, the evaluation result of public transportation vehicle dispatching scheme under different transportation schemes can be obtained by considering the traffic conditions and situation, and the weather conditions and transport accidents. The vehicle scheduling program can be compared with the experiment results to provide managers with decision support, including transport decision-making program assessment, vehicle scheduling program assessment, transport emergency response plan assessment, decision-making program evaluation results of the three-dimensional display and other functions.

Assessing the current state of operation of urban public transport and predicting the future situation can provide a training environment for public transport management program plans. On the basis of the CPSS model of UPDTN, the evaluation experiment of public transportation management can be carried out, evaluated and optimized under the circumstance of sudden demand or in the case of general demand. The management plan is placed in the actual and various artificial transport scenes, then the implementation effects can be observed, including the establishment of the evacuation task, the completion of the effect of background transport impact factors such as the comprehensive evaluation index system, evacuation plan, to access the different operation results in the case of different needs.

V. Conclusions

This paper proposes Cyber-Physical-Social-System (CPSS) models of Urban Public Transport Dynamic Network

(UPTDN) to study the evolution characteristics of public transport behavior, to achieve passengers and buses' adaptive and collaborative optimization in different spatiotemporal domains, and to improve the passenger service level and buses scheduling's quality. Also, it can provide support for the theoretical research of CPSS, and application practices in other areas.

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