Decentralized Autonomous Operations and Organizations in TransVerse: Federated Intelligence for Smart Mobility

Chen Zhao, Xingyuan Dai, Yisheng Lv, *Senior Member, IEEE*, Jinglong Niu, and Yilun Lin

***Abstract*—Human and social factors are essential to transportation systems, yet top-down management fails to consider them sufficiently. Consequently, management strategies are not tailored to human needs and are inadequate in providing transportation intelligence. This article investigates a management architecture based on decentralized/distributed autonomous operations/organizations (DAOs) that considers both the technical and societal aspects in our transportation metaverse, TransVerse. This design maps people's transportation needs in physical space to their digital counterparts in cyberspace, utilizing blockchain technology to guarantee the secure exchange of information and ultimately bring about the Internet of Minds (IoM). With the federated intelligence that emerged in IoM, we can devise reliable and prompt traffic decisions by incorporating consensus, community voting, and smart contracts into the organizational, coordination, and execution structure. Details on operational procedures and key technologies are also covered. To demonstrate the efficacy of DAOs-based management, a case study of world model-driven cooperative signal control is provided, indicating its promising application in future transportation management.**

***Index Terms*—Artificial systems, computational experiments, parallel execution (ACP), blockchain, cyber–physical–social systems (CPSS), decentralized/distributed autonomous operations and organizations (DAOs), intelligent transportation systems (ITS).**

I. Introduction

URBAN transportation systems are fundamental infrastructures that support city operations and serve as primary carriers connecting various services, contributing significantly to economic growth, cultural exchange, and socio-ecological development [1]. The growth of cities and the resulting increase in population density has led to a greater demand for urban transportation, putting pressure on transportation systems to keep up. A plethora of research is being undertaken to investigate cutting-edge intelligent transportation systems (ITS) [2] technologies to bolster the capacity and effectiveness of transportation systems. Inadequate consideration for human and social factors is a flaw of such technology-driven solutions in modeling actual systems [3]. The modeling gap has caused a disconnect between the traffic model and the residents' needs, resulting in a solution that is not tailored to their travel plans.

The proliferation of mobile devices, such as mobile phones, vehicle terminals, and wearable devices, has resulted in individuals becoming more involved in urban transportation and acting as ubiquitous sensors for social activity [4], [5]. The Internet of Things (IoT) holds great promise for real-time monitoring of traffic conditions and timely decision making by connecting these devices and facilities to various networks [6], [7]. There is also a wealth of traffic-related information available on social media platforms, such as Twitter, Facebook, Sina microblog, and so on [8]. The social signals generated by these crowd-sourced social sensors [9], [10] can supplement traffic models by providing timely, comprehensive, and rich data on urban dynamics, social behavior, and traffic conditions. Consequently, it is necessary to devise a fresh perspective that incorporates both social signals and cutting-edge technologies, allowing technical and social intelligence to complement one another to create a more refined transportation intelligence.

Crafting solutions for complex systems like transportation systems necessitates considering the advancement of technologically driven cyberspace as well as the evolution of the social space enabled by social signals. When the two are tightly integrated, the scope of cyber–physical systems (CPS) [11] is broadened to cyber–physical–social systems (CPSS), and the object of management is stretched from Newtonian systems with Newton's laws to Mertonian systems with Merton's laws [12]. It achieves a shift from parsing-based modeling, analysis, and control to data-driven description, prediction, and prescription [13]. Currently, there is an increased interest in CPSS-related research and it is being implemented in numerous industries [14], including smart manufacturing [15], vehicle testing [16], and transportation

Manuscript received 15 November 2022; revised 8 December 2022; accepted 10 December 2022. Date of publication 21 December 2022; date of current version 17 March 2023. This work was supported in part by the National Key Research and Development Program of China under Grant 2020YFB2104001; in the part by the National Natural Science Foundation of China under Grant U1811463; and in part by the Science and Technology Development Fund, Macau, SAR, under Grant 0050/2020/A1. This article was recommended by Associate Editor F.-Y. Wang. *(Corresponding author: Xingyuan Dai.)*

Chen Zhao, Xingyuan Dai, and Yisheng Lv are with the School of Artificial Intelligence, University of Chinese Academy of Sciences, Beijing 100049, China, and also with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China (e-mail: xingyuan.dai@ia.ac.cn).

Jinglong Niu is with the Land-Based Unmanned Systems Research and Development Department, North Automatic Control Technology Institute, Taiyuan 030006, China.

Yilun Lin is with the Urban Computing Research Center, Shanghai AI Laboratory, Shanghai 200232, China.

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TSMC.2022.3228914.

Digital Object Identifier 10.1109/TSMC.2022.3228914

management [17]. As stated in [18], CPSS is the abstract and scientific name for the buzzword metaverses, and the latter shares all of the former's typical characteristics, implying that CPSS is equivalent to metaverses.

TransVerse is a federation of transportation metaverses comprised of various artificial transportation systems (ATS) [1], allowing a virtual space where all transportation participants, including humans, vehicles, and smart infrastructures, are connected via the Internet of Minds (IoM) [19]. These digital mappings are not only functional replicates of the physical world but with unlimited scalability [20]. They are closely tied to the physical space, blending and intertwining with each other to form an expansive space for smart mobility. Our long-time efforts on parallel transportation systems [21] have spawned the construction of DeCAST [22] in TransVerse, designed on the decentralized/distributed autonomous operations and organizations (DAOs) principle [23] and artificial systems, computational experiments, parallel execution (ACP) [24]. This design focuses on constructing various ATS with a specific purpose and subsequently utilizing virtual–reality interaction and parallel execution to directly or indirectly alter human intentions and behavior, steering the actual systems in the direction of the desired goals.

The research of TransVerse is still in its infancy, and further investigation is needed in the design and implementation of management models, particularly the process of collaboration based on social signals. Initially, this article provides an overview of the construction and operating procedures in TransVerse. Subsequently, a human-oriented management framework is constructed, relying on a reliable blockchain-based transport ecosystem [25]. This design incorporates consensus [26], community voting [27], and nonfungible tokens (NFTs) [28] as the decision basis, mechanisms, and incentives, and automates decision implementations via smart contracts [29]. The decision-making process is integrated into the structure of the organization, coordination, and execution (OCE) [30], enabling federated intelligence and decentralized/distributed autonomous organizations with decentralized/distributed operations. Moreover, the proposed architecture has been combined with the ACP approach, which transitions reactive control to on-demand proactive management, thus yielding a remarkable improvement in transportation intelligence. An example of cooperative signal control is also discussed to demonstrate DAOs-based management.

II. TransVerse for Transportation 5.0

The traditional definition of ITS [31] refers to the application of advanced science and technology to facilitate the connection between vehicles, roads, and users, thus forming a unified transportation system that is secure, economical, energy-efficient, and eco-friendly. The design concept focuses on the technical elements that have been the driving force behind the invention and implementation of numerous ITS technologies. Of these, the digital twin (DT) [32] technology has attracted a great deal of attention as a potentially revolutionary advancement. It all started with NASA's Apollo project and has since been adopted in a variety of industries, such as smart manufacturing [33], driver assistance [34], motion control [35], and more. This technology enables the digital replication of physical entities (like roads, buildings, and infrastructure), the simulation of various events (like the weather, seasonal changes, and accidents) in real time, and the tracking and management of them throughout their life cycle [36]. Obviously, the core design of DT is in accordance with Newton's laws, with the goal of predicting and controlling the behavior of entities in CPS [37].

However, people are generally considered passive entities in DT while their active involvement is disregarded, leading to DT's struggles in addressing uncertainty, diversity, and complexity (UDC) in CPSS caused by social factors [20], [38]. Comprehending the complexities of human subjective behaviors can be advantageous in formulating wise choices in transportation systems. For example, as commuters fill the roads during peak hours, the roads become increasingly congested; conversely, they are much less crowded while people are at their jobs [39], [40], [41]. People's lifestyles are so intertwined with transportation systems that it is obvious that social factors are as important, if not more important, than technological ones in transportation advancement and evolution [42], [43]. Subsequently, the proposal of transportation 5.0 [44] was put forth, with citizens taking an active role in the detection, communication, computation, regulation, and oversight of ITS.

Transportation 5.0 has prompted a paradigm shift in the definition of ITS, switching from a technical focus to a more people-oriented one, as well as a transformation of the research field from CPS to the extended CPSS termed TransVerse. As demonstrated in Fig. 1, it emphasizes six types of intelligence ("6I") [45]: 1) cognitive; 2) parallel; 3) crypto; 4) federated; 5) social; and 6) ecological intelligence. The "6I" overhauls ITS from feature-based engineering design to scenario-oriented transportation ecology, thus making it possible to reach the "6S" goals for the creation and sustainability of smart cities: personal safety in the physical world [46], information security in the cyber world [47], environmental sustainability in ecological world [48], sensitivity to individual requirements [49], service for all, and smartness in all.

Various reliable and trustworthy scenario-oriented ATS must be built in TransVerse for computational experiments [50]. Existing ITS infrastructure and technologies, such as spatial topographic data integration [51] and dynamic social data collection [52], can all contribute to the scenario-building processes. After integrating static and dynamic data, a methodology for ensuring scenario trustworthiness via calibration and certification (C&C) as well as verification and validation (V&V), i.e., *scenarios engineering* [53], must be established. The tool can be used to align and supplement multimodal datasets [54], [55], and when combined with augmentation techniques like generative adversarial networks (GANs) [56], [57] or diffusion models [58], it can help to alleviate data imbalance. When these techniques are combined, we would get clean and rich data that can be used to render immersive virtual scenes. These scenario-based ATS can map

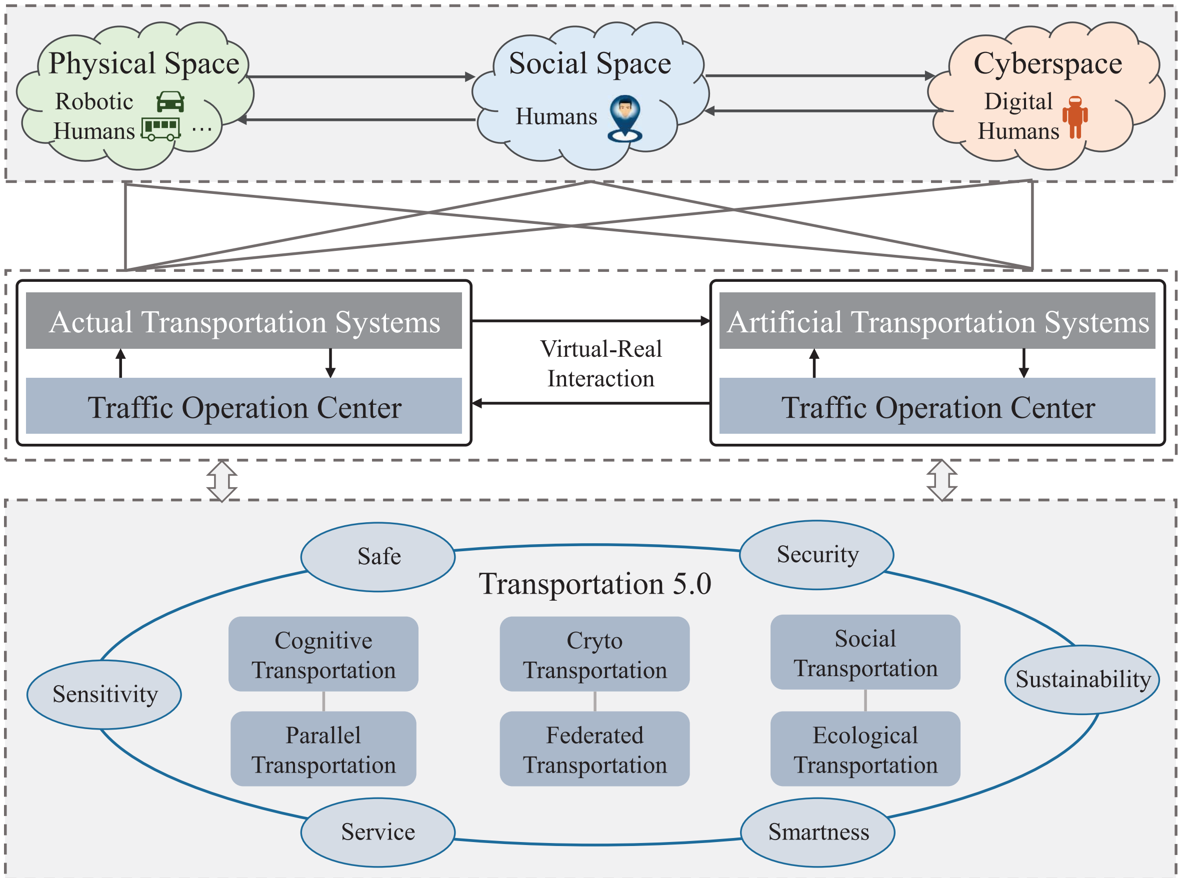

Fig. 1. TransVerse for Transportation 5.0: basic framework and operating processes.

real-time evolution as well as simulate future events, potentially assisting organizations in making better decisions about allocating transportation resources and responding to changes. Obviously, TransVerse provides a comprehensive and broad cyberspace for digital simulation and city management.

TransVerse operates on the basis of the continuous interactions between human behaviors and their surroundings, which are conscious logical actions rather than reactive responses. Human behavior cannot be understood through individual analysis alone, but must be viewed in the wider context of social interaction [59], [60]. According to *Praxeology*, behavior is an inherent component of life, with the physical body manifesting the behavior and the soul being accountable for the decision. As the era of intelligence has unfolded, it has expanded the capacities of humanity: robotic humans (RHs) are physical extensions of the body that can liberate us from mundane, tedious, or dangerous tasks, while digital humans (DHs) [61] are digital counterparts of people in cyberspace that greatly extend human cognitive activities. Their communication can range from one-to-one, one-to-many, or many-to-one, depending on the complexity of the task and the amount of computation needed. Human–computer interaction technology [62], [63] connects human activities across multiple spaces, substantially increasing human capabilities and transforming our lifestyle: being for the physical space, becoming of the social space, and believing in the cyberspace [18], [20].

It is believed that humans prioritize their decisions, thus allowing them to negotiate or trade and consequently create various intricate activities within our society [64]. The research of this branch of human behavior, commonly referred to as *Catallactics*, focuses on the order that emerges when individual economies operate in a free market system. The theory has been adapted as a management philosophy for the decentralized/distributed autonomous operations in TransVerse, enabling decentralized/distributed organizations and federated intelligence for smart mobility. An example of travel scheduling [65] is given in Fig. 2. People make proposals or express their desired travel plans, such as "I need to get to a specific location by 8 a.m." These ideas are transmitted to the relevant DHs with human–machine interaction commands (verbal, textual, pictorial, etc.), which provide the DHs with the necessary prompts to comprehend the task [66]. The introduction of blockchain and Web 3.0 has enabled DHs to be grouped into decentralized autonomous organizations and interact with one another to disseminate knowledge, creating an IoM. In TransVerse, the intangible elements of attention and trust are rendered into marketable commodities in cyberspace or markers used to gauge the potential of plans [67], [68]. Everyone can propose a mobility solution, discuss it in the IoM, rank the various options, and vote for the most productive, sustainable, and affordable option. The smart contracts will register the voting results, and RHs (such as self-driving cars or unmanned buses) will be assigned travel plans to ensure

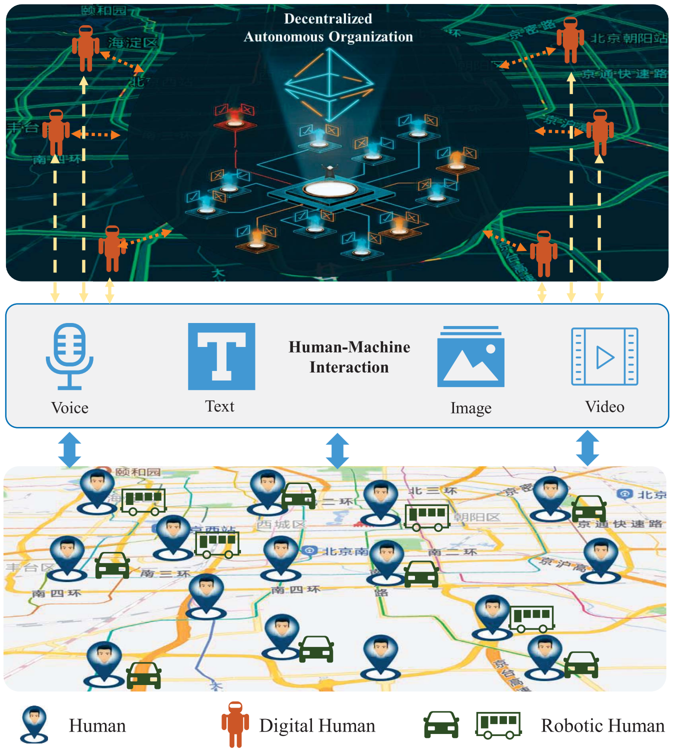

Fig. 2. Example of the DAOs-based travel scheduling in TransVerse.

the transportation resources are maximized in the physical space. To accomplish the process outlined above, we must have a reliable transport ecosystem as well as an effective organizational structure.

III. Overall Framework and Operational Processes

A. DAOs-Based Management Architecture in TransVerse

TransVerse has been designed with a DAOs-based management structure, as demonstrated in Fig. 3. The components of this design include the underlying infrastructures, decentralized operations, and organizations. They do not operate in isolation, but rather interact and collaborate with one another to spark management model innovations: decentralized, distributed, autonomous, automated, organizational, and operational [30]. With DAOs-based management, decisions concerning urban governance and transportation tasks are primarily made through collective participation and federated intelligence, providing a better alternative to traditional hierarchical management structures and specialist-driven decisions, consequently improving the effectiveness and dependability of ITS.

1) Underlying Infrastructures: Effective transportation organization management hinges on the ability to make sound decisions, which necessitates reliable data and trust in the formation and execution. Nonetheless, data asymmetry and trust asymmetry present major hindrances to further progress in ITS and organizational management reform [69]. The data asymmetry highlights the immense disparity in transportation information accessible to travelers. There is also a significant discrepancy between the availability of transportation resources and the demand for them [70]. This imbalance in the space–time relationship between the two has a significant impact on the daily lives of many individuals, especially those residing in urban areas. Trust asymmetry exists due to a variety of factors, including the protection of private information, trust levels that differ, and disparities in authority and accountability [71]. This can lead to a lack of trust between parties, creating barriers to effective communication, collaboration, and decision making. Moreover, trust and data usually go hand in hand: trust is built through the accumulation of data, thereby fostering a continuous exchange of information [72].

Through TransVerse, a blockchain-based platform, users are able to communicate their journey plans, insights, and assumptions. By fusing these federated data together, an IoM is created which eliminates data asymmetry and is then disseminated across blockchain networks [73], [74]. Blockchain technology ensures that long-term city development is achieved through consensus, enforces transportation regulations, and encourages democratic governance with token incentives and community voting, as well as automating processes via smart contracts. This process is highly reliable, open to public scrutiny, and verifiable for accuracy, thus eliminating trust asymmetry. To handle the challenge of some essential raw data being unable to pass through transportation blockchain networks, we can take advantage of federated learning (FL) [75] and multiparty secure computation (MPSC) [76] to construct a decision model with federated data and expedite the process with cloud/edge computing systems. The trained foundation models [22] can be applied to new scenarios and tasks, circumventing the issue of "reinventing the wheel."

2) Decentralized Operations: The consensus protocol is critical for eliminating trust asymmetry in blockchain networks and ensuring the reliability of decision-making processes in TransVerse. Various consensus algorithms are employed in blockchain networks [77], with the most popular ones being proof of work (POW), proof of stake (POS), delegated POS (DPOS), ripple protocol consensus algorithm (RPCA), practical Byzantine fault tolerance (PBFT), and delegated Byzantine fault tolerance (DBFT). Each option has its own pros and cons, making it necessary to find the best compromise when customizing a consensus mechanism applicable to transportation management, as this will determine the path ahead. It can also be crafted to include existing regulatory regulations, resulting in distributed monitoring for everyone. This ensures that decisions are made in accordance with the regulations and standards set forth by governing bodies, allowing for more secure and reliable transactions.

TransVerse facilitates collaboration among users in a federated manner, granting them the capability to initiate proposals, cast votes and assign tasks, enabling decentralized/distributed operations [78]. To guarantee a positive result, it is imperative to select an appropriate voting mechanism based on the consensus protocol that specifies who is eligible to vote and the voting effect on the shared administration. During the decision-making process, NFTs are employed to foster cooperative gaming [79] among multiple participants and to direct

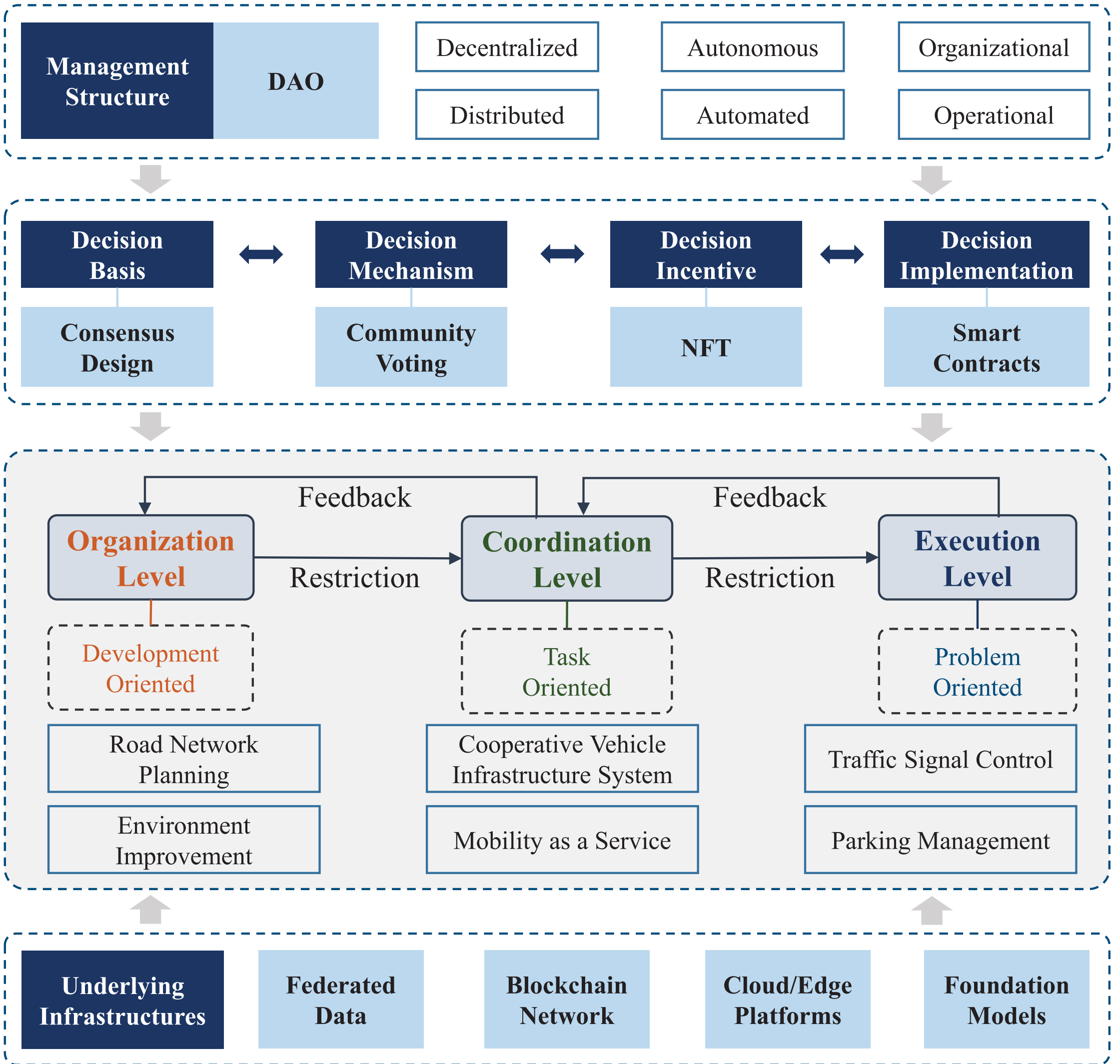

Fig. 3. DAOs-based management architecture in TransVerse.

their individual travel intentions to promote overall transportation accessibility. Due to the varying effects of managerial decisions on different individuals and levels, it is no longer feasible to gauge them using traditional homogeneous incentives; instead, using economic incentives represented by NFTs is a more effective way to reward members with an irreplaceable and nontransferable form of compensation [80]. NFTs combined with nonmonetary incentives like reputation, trust, and attention can satisfy the requirements of various participants and can be distributed based on personal contributions to DAOs [81], fostering federated intelligence.

TransVerse leverages smart contracts to automatically implement decisions encoded onto the blockchain network, ensuring decentralization and immutability. Initially, smart contracts are usually designed with traffic management rules and travel intent agreements, which are then translated into executable "If-Then" codes for DAOs [82]. Upon the initiation of DAOs, the smart contracts are adapted and supplemented based on the results of distributed voting [69]. In TransVerse, an assemblage of smart contracts has been programmed and generated that log access rights, trigger stipulations, communication laws, and operation techniques; these are packed into distinct agents that can constantly observe trigger conditions and perform autonomously without any external intervention, guaranteeing the efficiency and credibility of entire decision-making processes.

3) Decentralized Organizations: TransVerse's DAO-based management architecture establishes a novel operation paradigm that facilitates data and information transmission while protecting the privacy and lowering the cost of trust. It also enables decentralized autonomous organizations in ITS when combined with the OCE structure [30], as demonstrated in Fig. 3. The organization layer is concerned with urban development initiatives such as road network design or environmental enhancements. These initiatives are critical to the growth and sustainability of our cities, as well as the creation of a healthy and vibrant urban environment. Through weaving these long-term urban development initiatives into the design of the consensus mechanism in DAOs, we can consciously steer the behavior of all involved to reach our desired future. The coordination layer is in charge of collaborative projects, such as the development of a cooperative vehicle–infrastructure system (CVIS) [83] and the provision of mobility as a service (MaaS) [84]. Blockchain creates a trustworthy platform for multiple users to easily exchange data, removing information barriers and allowing users to make collective decisions through a voting system. This promotes smarter mobility and makes better use of transportation resources. The execution layer has an emphasis on problem solving, with smart contracts used to autonomously create solutions, ensuring swift operation. The three layers work together to ensure the smooth operation of TransVerse's decentralized organizations and to move us closer to a "6S" transportation system.

B. ACP-Based Operational Processes

By leveraging blockchain technology, we have developed decentralized artificial transportation systems that abide by consensus protocols and are operated automatically through smart contracts without external disturbance or disruption. This has the potential to transform social transportation from a passive framework to a proactive system that can be tracked, forecasted, and regulated. The ACP approach is combined the DAOs-controlled organizational architecture with these blockchain-driven "digital labs" conducting a variety of "What-If" computation experiments [85]. Rather than simply adhering to predetermined "If-Then" regulations, it grants smart contracts the capability to think critically about unknown circumstances and make decisions independently [86]. Smart contracts will be encapsulated as agents that will assist traffic management by providing intelligent matching, decision recommendation, and proactive prescription for actual transportation systems. Based on the type of interaction, the mode can be divided into three distinct categories.

1) Experimentation and Evaluation: In this mode, we can develop tailored scenarios in TransVerse for specific issues and execute multiple recurring tests to acquire individualized and precise understanding. For example, the number of scenarios and mileage available for testing autonomous driving on real roads is always limited due to safety and practical considerations. TransVerse provides an unparalleled reliable source of user data that can be used to construct a variety of traffic scenarios, particularly intricate, extreme, and hazardous ones [16]. Extensive experimentation and evaluation within such virtual scenarios are advantageous for identifying potential risks, devising effective safety measures, and improving the dependability of autonomous driving systems.

2) Control and Management: TransVerse has evolved into a comprehensive digital governance platform for smart cities in this mode, allowing us to manipulate reality with virtuality, optimize transportation resource utilization, and make more informed decisions to improve citizens' quality of life. All participants have been linked together through blockchain networks, where they can collaborate and use the combined strength of their shared knowledge and resources to gain federated intelligence. Smart contracts will be designed to incorporate this collective intelligence, which could quickly identify and recommend the best solutions to ongoing traffic situations in actual transportation systems [87].

3) Learning and Training: In this mode, TransVerse provides an invaluable learning space, delivering customized educational courses that simulate real-world scenarios to hone the abilities of traffic operators. Through simulations of real-world experiences with human–machine technology, TransVerse equips learners with the aptitude to be flexible and rapidly respond to situations in the real world. The platform also facilitates designers in constructing and customizing programs to fit their trainers' distinctive requirements, thereby generating an immersive and captivating educational experience. For example, by using three dimensional (3-D) analysis of vehicle accidents in cyberspace, it is possible to create a standardized digital database, empowering traffic professionals to handle emergencies in a timely and competent manner [88].

IV. Key Technologies

A. Communication Networks

The progress of communication technology reflects the advancement of human civilization, ranging from beacons, stagecoaches, wireless telegraphy, landlines, and mobile phones. Nowadays, data transmission is no longer confined to just the communication between people, but has extended to encompass the communication between people and objects, as well as between objects themselves. This phenomenon has opened up a new world of possibilities, allowing us to develop more efficient and effective ways of interacting with our surroundings, such as IoT, Internet of Vehicles (IoV) [75], and CVIS. These communication networks act as a bridge for the sharing of information, enabling people and organizations to share data with ease, reducing cognitive bias and paving the way for TransVerse's development. On this foundation, we can construct an IoM that unifies perceptions and coordinates needs so that we can make more informed decisions.

B. Computating Resources

To effectively utilize TransVerse, a high-performance computing resource is required for the management of large data sets, the development of complex scenarios, the operation of a blockchain platform, and the construction of computational models. Following the design principle of "local simple remote complex" [89], we typically use both cloud and edge servers to protect the privacy and manage real-time traffic. Data collected from local devices, such as induction loops, traffic cameras, and floating cars, are stored in edge servers located near the devices. This data can be used to train small models on edge servers to handle tasks in the region, and we can iterate on updates using the most recent data [68]. This ensures both continuous monitoring and adaptive control. Data between different edge servers is generally kept separate for security reasons; however, the disparity in computing power in different areas can be remedied by transmitting the model parameters. We can integrate the requirements of varying edge servers on cloud servers to provide long-term planning guidance for some collaborative tasks [90].

C. AI Technologies

All aspects of the TransVerse are touched by AI technologies, from vehicle recognition to traffic flow prediction, traffic scenario generation, driver fatigue analysis, human–computer interaction voice recognition, and beyond [91]. It is evident that AI is a vital component of the construction of TransVerse. Foundation models, in particular, have revolutionized problem-solving by transitioning from task-specific intelligence to scenarios-oriented generic intelligence, resulting in greater adaptability and productivity. Across various disciplines, there have been successful applications, such as BERT and GPT-3 in natural language processing, VMoE and ViT in visual processing, DALL·E in text-generated images, Make-A-Video in video models, and Gato in generalist agent. It is anticipated that transportation foundation models will be critical components in the successful deployment of TransVerse in the foreseeable future [22].

D. Scenarios-Building Technologies

Scenarios-building technologies provide the digital backbone for the construction of TransVerse. Spatial topographic data can be obtained from geographic information systems (GISs), high-definition maps (HD-Maps), radar and laser point clouds, building information modeling (BIM), and remote sensing images (RS). Spatiotemporal dynamic data can incorporate multiple sensors, IoT, Vehicle-to-Everything (V2X), social media, etc. Subsequently, a game engine must be employed to present the scene; Epic and Unity are the two most widely employed game engines, primarily used for DH creation, game design, and animation. To keep track of transportation infrastructure throughout its lifecycle and digitally represent its physical and functional properties, BIM 3-D modeling technology is essential. Real-time rendering is necessary to create an engaging visual experience for transport participants, where Microsoft Flight Simulator is a shining example [88]. By merging big data, cloud computing, and AI, scene-building technology in the future will be able to generate models autonomously and give TransVerse participants expeditious and easy-to-use tools.

E. Ecology Technologies

The ecological foundation of TransVerse mainly refers to blockchain-based DAOs [36]. Blockchain is a revolutionary technology that utilizes distributed data storage, peer-to-peer transmission, consensus mechanisms, and cryptographic algorithms to offer a secure, decentralized platform for data exchange. It is an innovative way to store and transfer data securely, as it relies on a distributed network of nodes, which must all agree on the data before storing it. Additionally, its cryptographic algorithms offer a high level of security, making it virtually impossible to alter or tamper with the data. Blockchain technology has the potential to revolutionize the way data is exchanged, stored, and secured. This technology facilitates a secure and decentralized platform for transportation participants to communicate and log decisions through smart contracts [29], providing a "code is trust" approach to governance. Due to its singularity, NFTs are sought-after and can be used to spur involvement from all participants of the TransVerse, thus incentivizing decisions and actively contributing to the growth of the platform.

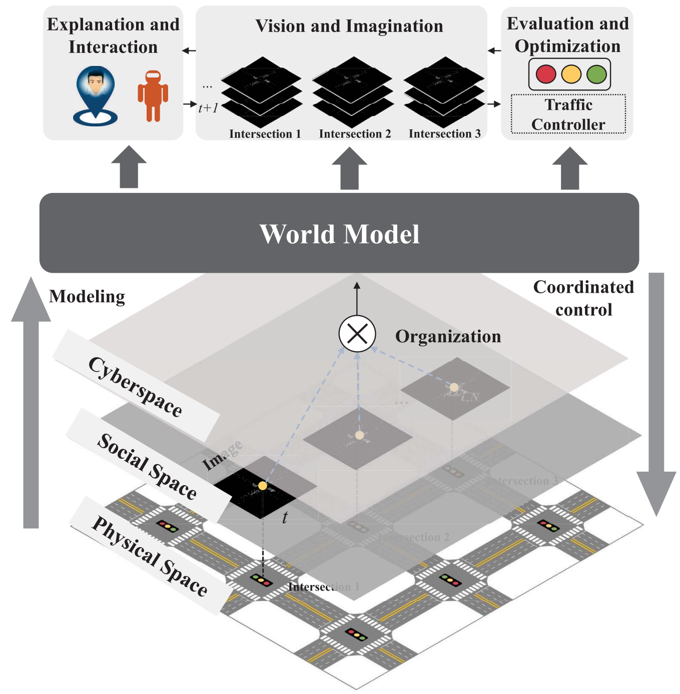

Fig. 4. Architecture of world-model-driven coordinated traffic signal control.

F. Interaction Technologies

TransVerse is a digital platform that facilitates user-to-user and user-to-environment interactions in a virtual transportation space [46]. Designing interactive digital products, systems, environments, and services with the goal of creating immersive virtual reality experiences is the purpose of interaction technology. XR technology (including VR, AR, and MR) has been created to provide users with a way to access the metaverse. This virtual reality program could be of great assistance in driver instruction [92]. With the combination of TransVerse and tourism, people are now able to witness the magnificence of the landscape from the comfort of their own homes.

V. Case Study

To demonstrate the concept of DAOs-based traffic management with foundation models, we present a case study on coordinated traffic signal control [93]. In this case, the world model is a prototype of the transportation foundation model that operates as a DAO. Fig. 4 depicts the architecture of world model-driven cooperative traffic signal control. It gathers traffic information in the physical space, encourages social networking, and applies modeling and optimization in cyberspace to meet organizational consensus while providing decision interpretation and interactive services for people.

The world-model-driven coordinated traffic signal controller stands out from existing approaches such as fixed-time and adaptive controllers due to its three unique features. Initially, it can process a broad range of data, for example, images,

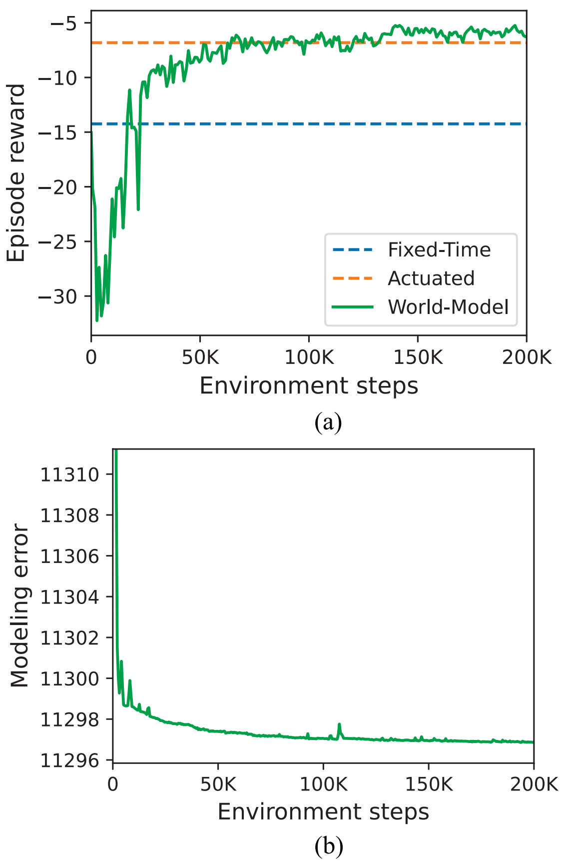

Fig. 5. Training curves over environment steps. (a) Evaluation rewards. (b) Modeling loss.

as opposed to just the vectors usually utilized in traditional traffic signal control [94]. The image contains various data which can be used to give more accurate control and optimize the performance of the road networks. The defining feature of the world model is its proficiency in extracting knowledge from image sequences and predicting traffic conditions over an extended period when utilizing a given strategy. On the one hand, this imaginative capability can be employed to develop robust control strategies through model-based planning. On the other hand, the world model can easily make it clear to traffic managers and participants why decisions were made, thus allowing for a human-in-the-loop approach to traffic control. Third, the global design can be established, connected, and augmented in an autonomously organized form on actual transportation systems, providing more adaptable and productive cooperative road management.

Our framework is divided into two steps: 1) training and 2) execution. The training procedure is entirely data driven. First, the intersection state is formalized as a series of images in which the vehicle positions are used as pixel points. The control strategy is then optimized by building a world model. The overall training approach is similar to DreamerV2 [95], and the optimization goal is to ensure a consensus of three intersections, i.e., to minimize road delays. After training, we have a world model and a control policy, with the model implementing an abstract representation of the traffic state and being able to predict future image-based traffic state changes for a given policy. For cooperative control, the policy network can generate a control command sent to the intersection controller in physical space.

TABLE I
CONTROL PERFORMANCE COMPARISON FOR DIFFERENT CONTROL POLICIES

Indexes	Fixed-Time Control	Actuated Control	World-Model Driven Control
Average Queue Length (veh)	1.817	0.869	0.714
Average Vehicle Speed (m/s)	6.186	6.558	6.590
Total Output Vehicles (veh)	564	608	613
Average Trip Delay (s)	114.25	102.03	101.88

To assess the efficacy of our research, we conduct experiments using a real dataset that contains 12 intersections, three of which we select to form an organization for cooperative control with the consensus of achieving the shortest delay at intersections [96]. Their training curves are shown in Fig. 5. We can see that the cumulative rewards (corresponding to consensus) of world-model-driven control increase during training and eventually outperform fixed-time and actuated control. Furthermore, the modeling error continues to decrease, indicating that the model gradually learns real-world knowledge and can reconstruct it in cyberspace. Following training, the world model outperforms the benchmark in all confidence control metrics, as shown in Table I. This is due primarily to its ability to model the world. As illustrated in Fig. 6, given the current moment and historical traffic state representations, the world model can predict the future traffic state of three intersections with high accuracy under the current strategy. This image-based prediction creates a natural human-in-the-loop paradigm that serves as a foundation for human decisions, making it easier to gain human trust. The foundation model, or future world model, can be integrated with various information, such as images, texts, and speech via multimodal fusion to further enhance the model's cognitive ability and meet people's diverse travel requirements.

VI. CONCLUSION

To tackle human and social elements in ITS, the focus of research has shifted from technology-focused CPS to TransVerse, a society-oriented transportation CPSS. This article outlines the constructions of TransVerse and illustrates its operational process. Traditional top-down management models have failed to effectively address the challenge of human-centered, distributed control in TransVerse, so this article proposes a DAOs-based management architecture as a solution. It creates a reliable social transportation ecosystem in order to form IOM among transportation participants. To facilitate trusted real-time decisions, we introduce a decision-making process to the OCE framework that includes consensus, community voting, and smart contracts. Furthermore, we integrate the framework with the ACP approach to enable models to proactively recommend solutions to traffic problems rather

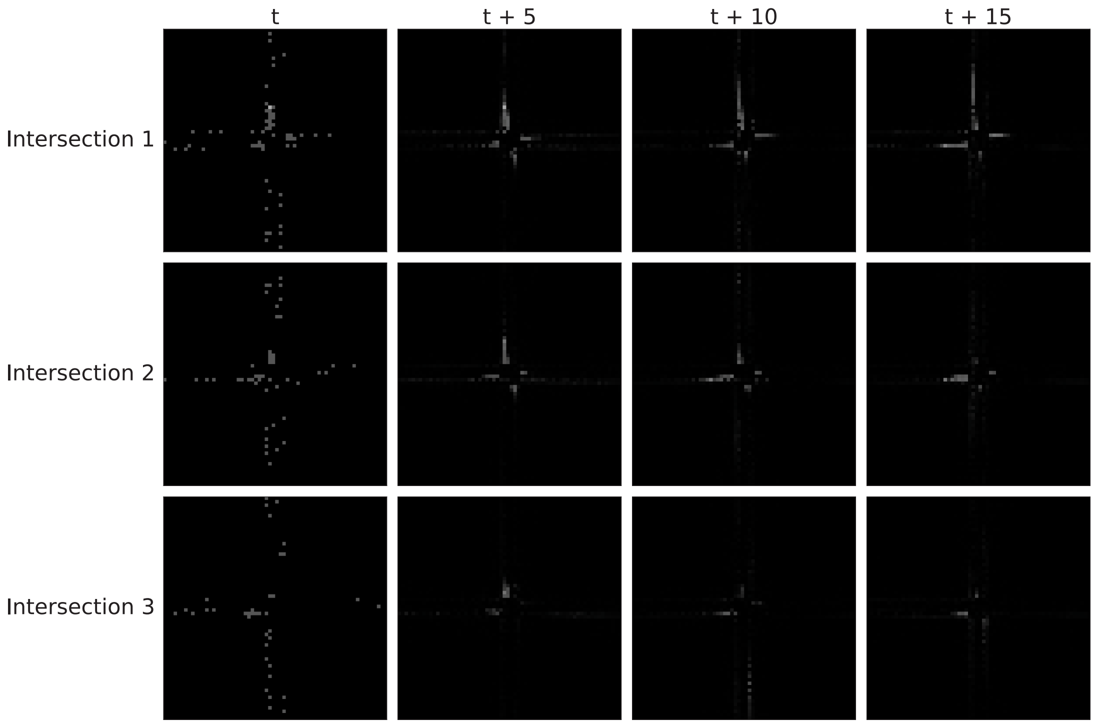

Fig. 6. Visualization of the predicted traffic states via world models given the traffic states at time *t*.

than simply reacting to them. Experiments with cooperative signal control attested to the efficacy of the DAOs-based decision-making process, indicating it as a potential solution for future transportation management.

REFERENCES

[1] F.-Y. Wang, "Parallel control and management for intelligent transportation systems: Concepts, architectures, and applications," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 630–638, Sep. 2010.

[2] J. Zhang, F.-Y. Wang, K. Wang, W.-H. Lin, X. Xu, and C. Chen, "Data-driven intelligent transportation systems: A survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 1624–1639, Dec. 2011.

[3] H. Lu et al., "Social signal-driven knowledge automation: A focus on social transportation," *IEEE Trans. Computat. Social Syst.*, vol. 8, no. 3, pp. 737–753, Jun. 2021.

[4] Q. Kong, W. Mao, G. Chen, and D. Zeng, "Exploring trends and patterns of popularity stage evolution in social media," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 10, pp. 3817–3827, Oct. 2020.

[5] H. Zahid, T. Mahmood, A. Morshed, and T. Sellis, "Big data analytics in telecommunications: Literature review and architecture recommendations," *IEEE/CAA J. Automatica Sinica*, vol. 7, no. 1, pp. 18–38, Jan. 2020.

[6] G. Fortino, C. Savaglio, G. Spezzano, and M. Zhou, "Internet of Things as system of systems: A review of methodologies, frameworks, platforms, and tools," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 1, pp. 223–236, Jan. 2021.

[7] P. Watta, X. Zhang, and Y. L. Murphey, "Vehicle position and context detection using V2V communication," *IEEE Trans. Intell. Veh.*, vol. 6, no. 4, pp. 634–648, Dec. 2021.

[8] Y. Lv, Y. Chen, X. Zhang, Y. Duan, and N. L. Li, "Social media based transportation research: The state of the work and the networking," *IEEE/CAA J. Automatica Sinica*, vol. 4, no. 1, pp. 19–26, Jan. 2017.

[9] H. Lin, S. Garg, J. Hu, G. Kaddoum, M. Peng, and M. S. Hossain, "Blockchain and deep reinforcement learning empowered spatial crowdsourcing in software-defined Internet of Vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 6, pp. 3755–3764, Jun. 2021.

[10] Y. Wang, W. Dai, Q. Jin, and J. Ma, "BciNet: A biased contest-based crowdsourcing incentive mechanism through exploiting social networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 8, pp. 2926–2937, Aug. 2020.

[11] D. Ding, Q.-L. Han, X. Ge, and J. Wang, "Secure state estimation and control of cyber-physical systems: A survey," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 1, pp. 176–190, Jan. 2021.

[12] F.-Y. Wang, "The emergence of intelligent enterprises: From CPS to CPSS," *IEEE Intell. Syst.*, vol. 25, no. 4, pp. 85–88, Jul./Aug. 2010.

[13] L. Li, Y. Lin, N. Zheng, and F.-Y. Wang, "Parallel learning: A perspective and a framework," *IEEE/CAA J. Automatica Sinica*, vol. 4, no. 3, pp. 389–395, Jul. 2017.

[14] J. J. Zhang et al., "Cyber-physical-social systems: The state of the art and perspectives," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 3, pp. 829–840, Sep. 2018.

[15] J. Yang, X. Wang, and Y. Zhao, "Parallel manufacturing for industrial metaverses: A new paradigm in smart manufacturing," *IEEE/CAA J. Automatica Sinica*, vol. 9, no. 12, pp. 2063–2070, Dec. 2022.

[16] L. Li et al., "Parallel testing of vehicle intelligence via virtual-real interaction," *Sci. Robot.*, vol. 4, no. 28, p. eaaw4106, 2019.

[17] X. Dai et al., "Parallel intelligence in parallel transportation systems: Description, prediction and prescription," *J. Intell. Sci. Technol.*, vol. 1, no. 3, pp. 17–21, 2021.

[18] F.-Y. Wang, "Parallel intelligence in metaverses: Welcome to Hanoi!" *IEEE Intell. Syst.*, vol. 37, no. 1, pp. 16–20, Jan./Feb. 2022.

[19] F.-Y. Wang, Y. Yuan, J. Zhang, R. Qin, and M. H. Smith, "Blockchainized Internet of Minds: A new opportunity for cyber–physical–social systems," *IEEE Trans. Computat. Social Syst.*, vol. 5, no. 4, pp. 897–906, Dec. 2018.

[20] X. Wang, J. Yang, J. Han, W. Wang, and F.-Y. Wang, "Metaverses and DeMetaverses: From digital twins in CPS to parallel intelligence in CPSS," *IEEE Intell. Syst.*, vol. 37, no. 4, pp. 97–102, Jul./Aug. 2022.

[21] F.-Y. Wang, "CAST lab: A cyber-social-physical approach for traffic control and transportation management," Intell. Control Syst. Eng. Center Chin. Acad. Sci., Beijing, China, Rep. #1999-12-1, 1999.

[22] C. Zhao, Y. Lv, J. Jin, Y. Tian, J. Wang, and F.-Y. Wang, "DeCAST in TransVerse for parallel intelligent transportation systems and smart cities: Three decades and beyond," *IEEE Intell. Transp. Syst. Mag.*, vol. 14, no. 6, pp. 6–17, Nov./Dec. 2022.

[23] F.-Y. Wang, "The DAO to MetaControl for metaSystems in metaverses: The system of parallel control systems for knowledge automation and control intelligence in CPSS," *IEEE/CAA J. Automatica Sinica*, vol. 9, no. 11, pp. 1899–1908, Nov. 2022.

[24] F.-Y. Wang, "Toward a paradigm shift in social computing: The ACP approach," *IEEE Intell. Syst.*, vol. 22, no. 5, pp. 65–67, Sep./Oct. 2007.

[25] C. Zhao et al., "Decentralized autonomous federation of transportation metaverses: A new ecosystem for transportaion intelligence," *Int. J. Intell. Control Syst.*, vol. 2, no. 2, pp. 1–6, 2022.

[26] D. Huang, X. Ma, and S. Zhang, "Performance analysis of the Raft consensus algorithm for private blockchains," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 1, pp. 172–181, Jan. 2020.

[27] D. Xu, W. Shi, W. Zhai, and Z. Tian, "Multi-candidate voting model based on blockchain," *IEEE/CAA J. Automatica Sinica*, vol. 8, no. 12, pp. 1891–1900, Dec. 2021.

[28] R. Qin, J. Li, X. Wang, J. Zhu, Y. Yuan, and F.-Y. Wang, "NFT: Blockchain-based non-fungible token and applications," *Chin. J. Intell. Sci. Technol.*, vol. 3, no. 2, pp. 234–242, 2021.

[29] S. Wang, L. Ouyang, Y. Yuan, X. Ni, X. Han, and F.-Y. Wang, "Blockchain-enabled smart contracts: Architecture, applications, and future trends," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 49, no. 11, pp. 2266–2277, Nov. 2019.

[30] F.-Y. Wang, "Parallel management: The DAO to smart ecological technology for complexity management intelligence," *Acta Automatica Sinica*, vol. 48, no. 11, pp. 2655–2669, 2022.

[31] M. Veres and M. Moussa, "Deep learning for intelligent transportation systems: A survey of emerging trends," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 8, pp. 3152–3168, Aug. 2020.

[32] Q. Wang, W. Jiao, P. Wang, and Y. Zhang, "Digital twin for human-robot interactive welding and welder behavior analysis," *IEEE/CAA J. Automatica Sinica*, vol. 8, no. 2, pp. 334–343, Feb. 2021.

[33] J. Leng et al., "ManuChain: Combining permissioned blockchain with a holistic optimization model as bi-level intelligence for smart manufacturing," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 1, pp. 182–192, Jan. 2020.

[34] Z. Wang et al., "Driver behavior modeling using game engine and real vehicle: A learning-based approach," *IEEE Trans. Intell. Veh.*, vol. 5, no. 4, pp. 738–749, Dec. 2020.

[35] Z. Wang, Y. Bian, S. E. Shladover, G. Wu, S. E. Li, and M. J. Barth, "A survey on cooperative longitudinal motion control of multiple connected and automated vehicles," *IEEE Intell. Transp. Syst. Mag.*, vol. 12, no. 1, pp. 4–24, Apr. 2020.

[36] S. Liao, J. Wu, A. K. Bashir, W. Yang, J. Li, and U. Tariq, "Digital twin consensus for blockchain-enabled intelligent transportation systems in smart cities," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 11, pp. 22619–22629, Nov. 2022.

[37] F.-Y. Wang, Y. Li, W. Zhang, G. Bennett, and N. Chen, "Digital twin and parallel intelligence based on location and transportation: A vision for new synergy between the IEEE CRFID and ITSS in cyberphysical social systems," *IEEE Intell. Transp. Syst. Mag.*, vol. 13, no. 1, pp. 249–252, Jan. 2021.

[38] J. Leng et al., "Blockchain-secured smart manufacturing in industry 4.0: A survey," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 1, pp. 237–252, Jan. 2021.

[39] Y. Lv, Y. Duan, W. Kang, Z. Li, and F.-Y. Wang, "Traffic flow prediction with big data: A deep learning approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 865–873, Apr. 2015.

[40] X. Li, Y. Liu, K. Wang, and F.-Y. Wang, "A recurrent attention and interaction model for pedestrian trajectory prediction," *IEEE/CAA J. Automatica Sinica*, vol. 7, no. 5, pp. 1361–1370, Sep. 2020.

[41] M. Koschi and M. Althoff, "Set-based prediction of traffic participants considering occlusions and traffic rules," *IEEE Trans. Intell. Veh.*, vol. 6, no. 2, pp. 249–265, Jun. 2021.

[42] X. Wang, X. Zheng, W. Chen, and F.-Y. Wang, "Visual human–computer interactions for intelligent vehicles and intelligent transportation systems: The state of the art and future directions," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 1, pp. 253–265, Jan. 2021.

[43] E. Herrera-Viedma et al., "Revisiting fuzzy and linguistic decision making: Scenarios and challenges for making wiser decisions in a better way," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 1, pp. 191–208, Jan. 2021.

[44] F.-Y. Wang, "Scanning the issue and beyond: Computational transportation and transportation 5.0," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 5, pp. 1861–1868, Oct. 2014.

[45] F.-Y. Wang, "The engineering of intelligence: DAO to I&I, C&C, and V&V for intelligent systems," *Int. J. Intell. Control Syst.*, vol. 1, no. 3, pp. 1–5, 2021.

[46] J. Nie, J. Yan, H. Yin, L. Ren, and Q. Meng, "A multimodality fusion deep neural network and safety test strategy for intelligent vehicles," *IEEE Trans. Intell. Veh.*, vol. 6, no. 2, pp. 310–322, Jun. 2021.

[47] D. Zhang, G. Feng, Y. Shi, and D. Srinivasan, "Physical safety and cyber security analysis of multi-agent systems: A survey of recent advances," *IEEE/CAA J. Automatica Sinica*, vol. 8, no. 2, pp. 319–333, Feb. 2021.

[48] Y. Zhou, X. C. Liu, R. Wei, and A. Golub, "Bi-objective optimization for battery electric bus deployment considering cost and environmental equity," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 4, pp. 2487–2497, Apr. 2021.

[49] M. Hasenjäger, M. Heckmann, and H. Wersing, "A survey of personalization for advanced driver assistance systems," *IEEE Trans. Intell. Veh.*, vol. 5, no. 2, pp. 335–344, Jun. 2020.

[50] N. Zhang, F.-Y. Wang, F. Zhu, D. Zhao, and S. Tang, "DynaCAS: Computational experiments and decision support for ITS," *IEEE Intell. Syst.*, vol. 23, no. 6, pp. 19–23, Nov./Dec. 2008.

[51] A. Kasmi, J. Laconte, R. Aufrere, D. Denis, and R. Chapuis, "End-to-end probabilistic ego-vehicle localization framework," *IEEE Trans. Intell. Veh.*, vol. 6, no. 1, pp. 146–158, Mar. 2021.

[52] Y. Lin et al., "Dynamic control of fraud information spreading in mobile social networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 6, pp. 3725–3738, Jun. 2021.

[53] X. Li, P. Ye, J. Li, Z. Liu, L. Cao, and F.-Y. Wang, "From features engineering to scenarios engineering for trustworthy AI: I&I, C&C, and V&V," *IEEE Intell. Syst.*, vol. 37, no. 4, pp. 18–26, Jul./Aug. 2022.

[54] Y. Liu, S. Cao, P. Lasang, and S. Shen, "Modular lightweight network for road object detection using a feature fusion approach," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 8, pp. 4716–4728, Aug. 2021.

[55] Y. Chen, Y. Lv, and F.-Y. Wang, "Traffic flow imputation using parallel data and generative adversarial networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 4, pp. 1624–1630, Apr. 2020.

[56] Y. Lv, Y. Chen, L. Li, and F.-Y. Wang, "Generative adversarial networks for parallel transportation systems," *IEEE Intell. Transp. Syst. Mag.*, vol. 10, no. 3, pp. 4–10, Jun. 2018.

[57] C. Ou and F. Karray, "Enhancing driver distraction recognition using generative adversarial networks," *IEEE Trans. Intell. Veh.*, vol. 5, no. 3, pp. 385–396, Sep. 2020.

[58] D. Kingma, T. Salimans, B. Poole, and J. Ho, "Variational diffusion models," in *Proc. Int. Conf. Adv. Neural Inf. Process. Syst.*, vol. 34, 2021, pp. 21696–21707.

[59] M. Xu et al., "Crowd behavior simulation with emotional contagion in unexpected multihazard situations," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 3, pp. 1567–1581, Mar. 2021.

[60] T. Liu, B. Tian, Y. Ai, and F.-Y. Wang, "Parallel reinforcement learning-based energy efficiency improvement for a cyber-physical system," *IEEE/CAA J. Automatica Sinica*, vol. 7, no. 2, pp. 617–626, Mar. 2020.

[61] P. Ye and F.-Y. Wang, "Parallel population and parallel human—A cyber-physical social approach," *IEEE Intell. Syst.*, vol. 37, no. 5, pp. 19–27, Sep./Oct. 2022.

[62] S. Kumar, C. Savur, and F. Sahin, "Survey of human–robot collaboration in industrial settings: Awareness, intelligence, and compliance," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 1, pp. 280–297, Jan. 2021.

[63] D. Xiong, D. Zhang, X. Zhao, and Y. Zhao, "Deep learning for EMG-based human–machine interaction: A review," *IEEE/CAA J. Automatica Sinica*, vol. 8, no. 3, pp. 512–533, Mar. 2021.

[64] X. Yang, G. Wang, H. He, J. Lu, and Y. Zhang, "Automated demand response framework in ELNs: Decentralized scheduling and smart contract," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 1, pp. 58–72, Jan. 2020.

[65] M. Morsali, E. Frisk, and J. Åslund, "Spatio-temporal planning in multi-vehicle scenarios for autonomous vehicle using support vector machines," *IEEE Trans. Intell. Veh.*, vol. 6, no. 4, pp. 611–621, Dec. 2021.

[66] X. Wang, Y. Guo, C. Bai, Q. Yuan, S. Liu, and J. Han, "Driver's intention identification with the involvement of emotional factors in two-lane roads," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 11, pp. 6866–6874, Nov. 2021.

[67] Y. Yuan and F.-Y. Wang, "Blockchain and cryptocurrencies: Model, techniques, and applications," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 48, no. 9, pp. 1421–1428, Sep. 2018.

[68] Z. Zhou, B. Wang, M. Dong, and K. Ota, "Secure and efficient vehicle-to-grid energy trading in cyber physical systems: Integration of blockchain and edge computing," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 1, pp. 43–57, Jan. 2020.

[69] G. Wang, J. Li, X. Wang, J. Li, Y. Yuan, and F.-Y. Wang, "Blockchain-based crypto management for reliable real-time decision-making," *IEEE Trans. Computat. Social Syst.*, early access, Oct. 17, 2022, doi: 10.1109/TCSS.2022.3211331.

[70] X. Ge, Q.-L. Han, L. Ding, Y.-L. Wang, and X.-M. Zhang, "Dynamic event-triggered distributed coordination control and its applications: A survey of trends and techniques," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 9, pp. 3112–3125, Sep. 2020.

[71] P. K. Singh, R. Singh, S. K. Nandi, K. Z. Ghafoor, D. B. Rawat, and S. Nandi, "Blockchain-based adaptive trust management in Internet of Vehicles using smart contract," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 6, pp. 3616–3630, Jun. 2021.

[72] M. Khari, A. K. Garg, A. H. Gandomi, R. Gupta, R. Patan, and B. Balusamy, "Securing data in Internet of Things (IoT) using cryptography and steganography techniques," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 50, no. 1, pp. 73–80, Jan. 2020.

[73] J. L. Li, G. Wang, X. Wang, J. Li, Y. Yuan, and F.-Y. Wang, "Crypto management: A novel organizational management model based on blockchain," *Chin. J. Intell. Sci. Technol.*, vol. 4, no. 2, pp. 145–156, 2022.

[74] H. Lu, Y. Tang, and Y. Sun, "DRRS-BC: Decentralized routing registration system based on blockchain," *IEEE/CAA J. Automatica Sinica*, vol. 8, no. 12, pp. 1868–1876, Dec. 2021.

[75] W. Y. B. Lim et al., "Towards federated learning in UAV-enabled Internet of Vehicles: A multi-dimensional contract-matching approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 8, pp. 5140–5154, Aug. 2021.

[76] M. Han, A. Wan, F. Zhang, and S. Ma, "An attribute-isolated secure communication architecture for intelligent connected vehicles," *IEEE Trans. Intell. Veh.*, vol. 5, no. 4, pp. 545–555, Dec. 2020.

[77] B. Hu, C. Zhou, Y.-C. Tian, X. Hu, and X. Junping, "Decentralized consensus decision-making for cybersecurity protection in multimicrogrid systems," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 4, pp. 2187–2198, Apr. 2021.

[78] J. Jiang, B. An, Y. Jiang, C. Zhang, Z. Bu, and J. Cao, "Group-oriented task allocation for crowdsourcing in social networks," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 7, pp. 4417–4432, Jul. 2021.

[79] C. Peng and W. Zhang, "Multiobjective dynamic optimization of cooperative difference games in infinite horizon," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 51, no. 11, pp. 6669–6680, Nov. 2021.

[80] F.-Y. Wang, R. Qin, Y. Yuan, and B. Hu, "Nonfungible tokens: Constructing value systems in parallel societies," *IEEE Trans. Computat. Social Syst.*, vol. 8, no. 5, pp. 1062–1067, Oct. 2021.

[81] J. Li, X. Ni, Y. Yuan, and F.-Y. Wang, "A novel GSP auction mechanism for dynamic confirmation games on Bitcoin transactions," *IEEE Trans. Services Comput.*, vol. 15, no. 3, pp. 1436–1447, May/Jun. 2022.

[82] S. Wang, W. Ding, J. Li, Y. Yuan, L. Ouyang, and F.-Y. Wang, "Decentralized autonomous organizations: Concept, model, and applications," *IEEE Trans. Computat. Social Syst.*, vol. 6, no. 5, pp. 870–878, Oct. 2019.

[83] Z. Yao, L. Shen, R. Liu, Y. Jiang, and X. Yang, "A dynamic predictive traffic signal control framework in a cross-sectional vehicle infrastructure integration environment," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 4, pp. 1455–1466, Apr. 2020.

[84] A. Bucchiarone, S. Battisti, A. Marconi, R. Maldacea, and D. C. Ponce, "Autonomous shuttle-as-a-service (ASaaS): Challenges, opportunities, and social implications," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 6, pp. 3790–3799, Jun. 2021.

[85] R. Qin, Y. Yuan, and F.-Y. Wang, "Blockchain-based knowledge automation for CPSS-oriented parallel management," *IEEE Trans. Computat. Social Syst.*, vol. 7, no. 5, pp. 1180–1188, Oct. 2020.

[86] L. Li, Y. Lv, and F.-Y. Wang, "Traffic signal timing via deep reinforcement learning," *IEEE/CAA J. Automatica Sinica*, vol. 3, no. 3, pp. 247–254, Jul. 2016.

[87] J. Jin, H. Guo, J. Xu, X. Wang, and F.-Y. Wang, "An end-to-end recommendation system for urban traffic controls and management under a parallel learning framework," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 3, pp. 1616–1626, Mar. 2021.

[88] S. Hasirlioglu and A. Riener, "A general approach for simulating rain effects on sensor data in real and virtual environments," *IEEE Trans. Intell. Veh.*, vol. 5, no. 3, pp. 426–438, Sep. 2020.

[89] F.-Y. Wang, "Agent-based control for networked traffic management systems," *IEEE Intell. Syst.*, vol. 20, no. 5, pp. 92–96, Sep./Oct. 2005.

[90] Z. Li, C. Chen, and K. Wang, "Cloud computing for agent-based urban transportation systems," *IEEE Intell. Syst.*, vol. 26, no. 1, pp. 73–79, Jan./Feb. 2011.

[91] Y. Ma, Z. Wang, H. Yang, and L. Yang, "Artificial intelligence applications in the development of autonomous vehicles: A survey," *IEEE/CAA J. Automatica Sinica*, vol. 7, no. 2, pp. 315–329, Mar. 2020.

[92] Y. Wang, Y. Ren, S. Elliott, and W. Zhang, "Enabling courteous vehicle interactions through game-based and dynamics-aware intent inference," *IEEE Trans. Intell. Veh.*, vol. 5, no. 2, pp. 217–228, Jun. 2020.

[93] J. Jin et al., "PRECOM: A parallel recommendation engine for control, operations, and management on congested urban traffic networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, pp. 7332–7342, Jul. 2022.

[94] M. Abdoos, "A cooperative multiagent system for traffic signal control using game theory and reinforcement learning," *IEEE Intell. Transp. Syst. Mag.*, vol. 13, no. 4, pp. 6–16, 2021.

[95] D. Hafner, T. P. Lillicrap, M. Norouzi, and J. Ba, "Mastering Atari with discrete world models," in *Proc. Int. Conf. Learn. Represent.*, 2020, pp. 1–26.

[96] J. Jin et al., "An agent-based traffic recommendation system: Revisiting and revising urban traffic management strategies," *IEEE Trans. Syst., Man, Cybern., Syst.*, vol. 52, no. 11, pp. 7289–7301, Nov. 2022.

Chen Zhao received the B.Eng. degree in automation from Changan University, Xi'an, China, in 2017, and the M.Sc. degree in control theory and control engineering from Nankai University, Tianjin, China, in 2020. He is currently pursuing the Ph.D. degree in computer applied technology with the University of Chinese Academy of Sciences, Beijing, China, and the Institute of Automation, Chinese Academy of Sciences, Beijing.

His research interests include intelligent transportation systems and multiagent deep reinforcement learning.

Xingyuan Dai received the Ph.D. degree in control theory and control engineering from the Institute of Automation, Chinese Academy of Sciences, Beijing, China, in 2022.

He is currently an Assistant Professor with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences. His research interest covers intelligent transportation systems, machine learning, and deep learning.

Yisheng Lv (Senior Member, IEEE) received the Ph.D. degree in control theory and control engineering from the Chinese Academy of Sciences, Beijing, China, in 2010.

He is a Professor with the State Key Laboratory for Management and Control of Complex Systems, Institute of Automation, Chinese Academy of Sciences. He is also with the University of Chinese Academy of Sciences, Beijing. His research interests include artificial intelligence for transportation, intelligent vehicles, and parallel traffic management and control systems.

Jinglong Niu received the Ph.D. degree in mechatronics engineering from Beihang University, Beijing, China, in 2019.

He is currently an Associate Research Fellow with the North Automatic Control Technology Institute, Taiyuan, China. His research interests include swarm robot cooperation and control, signal processing, and reinforcement learning.

Yilun Lin received the Ph.D. degree in control science and engineering from the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing, China, in 2019.

He is currently a Research Scientist and the Principal Investigator with the Urban Computing Research Center, Shanghai AI Laboratory, Shanghai, China. His research interests include social computing, urban computing, intelligent transportation systems, deep learning, reinforcement learning, and privacy-preserving computing.