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Research on 3D Visualization Design of Intelligent Transportation SandTable Empowered by Time Dimension

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Abstract: As a pivotal carrier bridging traffic theory and engineering practice, the rationality of design and completeness of data representation for traffic sand tables directly underpin the accuracy of scene restoration and the reliability of experimental outcomes. To address the inherent limitations of traditional intelligent traffic sand tables—including the "2D planarization and spatiotemporal information fragmentation" of trajectory data, as well as the lack of standardized design workflows and insufficient virtual-physical mapping adaptability in physical sand tables—this study centers on the core design innovation of "integrating the time dimension into 3D modeling". Guided by the systematic, practical, and visual thinking of industrial design, an "x-y-t" spatiotemporal three-dimensional coordinate system is constructed to enable the design and construction of a high-precision physical sand table. The research achieves spatiotemporal dynamic visualization of trajectory data through deep integration of the time axis and spatial axes. Adopting a full-lifecycle approach encompassing demand analysis, design, implementation, verification, and optimization, it plans the sand table's structural layout, equipment integration, human-computer interaction, and functional adaptation. Perception units such as V2X communication, millimeter-wave radar, and UWB positioning are integrated to establish a precise mapping relationship between digital models and the physical sand table. Experimental validation demonstrates that this design enhances the efficiency of spatiotemporal correlation recognition for trajectory data by 42%, with a digital-physical trajectory matching accuracy of 1.93 mm and a time synchronization error of ≤22 ms. It thus establishes a novel design paradigm for intelligent traffic sand tables characterized by "spatiotemporal integrated expression - high-precision physical design - precise virtual-physical mapping", offering innovative insights and practical solutions for the application of industrial design in the intelligent transportation domain.

Keywords: Intelligent Transportation Sand Table; Industrial Design; 3D Modeling; Time Dimension; Spatiotemporal Visualization; Standardized Construction; Virtual-Reality Mapping.

1. Introduction

1.1. Research Background

The acceleration of global urbanization and the exponential growth in motor vehicle ownership have led to unprecedented levels of complexity in urban transportation networks, resulting in critical bottlenecks such as traffic congestion, reduced transit efficiency, and frequent traffic accidents, which hinder urban logistics and residents' commuting experiences.[1] The rapid pace of urbanization globally is propelling the transformation of transportation systems toward intelligentization. The Intelligent Traffic Simulation Platform serves as a core tool for microscopic traffic scene modeling [2], technical validation, and instructional demonstration. Its design quality directly influences the efficiency of traffic-related research and the translation of findings into practical applications. Traditional intelligent traffic simulation platforms face notable limitations: in data representation, they focus solely on two-dimensional spatial trajectories, neglecting the dynamic temporal evolution, thereby impairing the intuitive visualization of spatiotemporal traffic flow patterns; users are required to interpret discrete datasets to reconstruct network conditions, contravening the principle of efficient information transmission. In physical implementation, the lack of systematic design processes results in base structures, road layouts, and equipment deployment primarily based on experiential judgment, leading to issues such as poor dimensional compatibility, equipment incompatibility, and maintenance challenges, which compromise the platform's capacity for high-precision experiments. Additionally, in virtual-physical integration, insufficient synchronization between digital models and physical sandbox elements results in low spatiotemporal fidelity, limiting the accurate recreation of dynamic scenarios and restricting practical utility.

As digital twin technology and edge computing increasingly integrate with industrial design, intelligent traffic sandbox simulations must transcend conventional design paradigms. The objective is to achieve comprehensive data representation, standardization, and precise virtual-real mapping, thereby establishing an innovative form that balances technological advancement with design rationality. Incorporating the temporal dimension into three-dimensional modeling, and employing standardized procedural methodologies for the visualization of spatiotemporal information and the systematic construction of physical sandbox models, emerges as a critical approach to addressing the limitations inherent in traditional sandbox design.

1.2. Current Status of Domestic and International Research

V2X communication technology, as the fundamental support for intelligent transportation systems, has recently become a focal point of research domestically and internationally. In the domain of international studies, Rakouth[3] et al. investigated implementation pathways of V2X within projects such as Japan's SMARTWAY and Europe's DriveC2X, utilizing dedicated short-range

communication (DSRC) based on IEEE 802.11p/WAVE standards, and verified the feasibility of integrating DSRC with 4G LTE cellular technology. Jung[4] et al. proposed a V2X-assisted autonomous driving system that enables real-timevehicle-to-vehicleand vehicle-to-infrastructure (V2I) data exchange, facilitating safe coordinated navigation through intersections. Hegde[5] et al. developed the Artery-C simulation framework, providing a standardized platform for performance evaluation of cellular-based V2X protocols. Alnasser[6] et al. concentrated on security challenges within V2X communication networks, emphasizing the importance of vehicular network security measures. Within China, Wei Wei[7] explored resource allocation issues in D2D/V2X communications, proposing an auction-based resource scheduling algorithm; Feng Yijia[8] integrated V2X transmission technologies with intelligent connected vehicle platoon trajectory planning, effectively enhancing roadway capacity and reducing vehicular energy consumption; Hu Yanru[9] analyzed techniques for updating side-link identifiers in 5G V2X communications to ensure reliable vehicular network connectivity; Luo Chunli[10] employed V2X technology to establish novel traffic flow models aimed at alleviating congestion. Overall, V2X technology has achieved significant advancements from theoretical validation to practical deployment; however, research gaps remain in multi-agent cooperative decision-making and low-carbon control integration within physical sandbox scenarios.

In the domain of intelligent transportation route optimization algorithms, research has evolved from traditional static methods to intelligent dynamic approaches. Conventional algorithms such as Dijkstra's[11] algorithm and A employ exhaustive or heuristic search techniques for shortest path determination but face limitations in accommodating dynamic traffic flows. In the realm of intelligent algorithms, Kumar[12] et al. proposed a traffic signal scheduling framework based on deep reinforcement learning to facilitate real-time signal timing optimization. Zhou Lihaolin[13] and colleagues enhanced density clustering methods to achieve precise identification of traffic flows in multi-airport terminal areas. Li Zongyang[14] developed an integrated intelligent connected vehicle traffic safety monitoring system incorporating vehicle-to-infrastructure cooperative path planning algorithms for obstacle avoidance. Furthermore, bio-inspired swarm intelligence algorithms, such as ant colony optimization and Boids flocking models, have garnered increasing attention for multi-vehicle cooperative path planning. Nonetheless, their validation in physical sandbox environments and adaptation to multimodal traffic flows remain areas for further investigation. The integration of large-scale models like LLama3 and LoRA fine-tuning techniques introduces new avenues for traffic decision-making, leveraging transformer architectures with self-attention mechanisms to capture global dependencies within traffic data, thereby enhancing decision accuracy.

Research on intelligent traffic simulation platforms concentrates on the integration of virtual and physical environments and multi-modal traffic management. Internationally, Moshe Ben-Akiva[15] et al. developed an integrated traffic simulation framework enabling precise prediction of traffic event durations; Miroslaw Gidlewski[16] et al. established a disturbance-sensitive model for vehicle lane-changing control, providing theoretical support for the dynamics simulation of simulation vehicles; Farag[17] et al. demonstrated the efficacy of cellular V2X technology in energy-efficient dynamic routing applications. Domestically, Honghong Xing[18] incorporated 5G communication technology into intelligent traffic simulators to enhance real-time data transmission; Xusheng Chen[19] proposed a multi-sensor fusion-based autonomous vehicle localization method to ensure vehicle positioning accuracy; some projects have achieved linkage between physical simulators and digital twins, yet challenges remain in spatiotemporal three-dimensional modeling, decentralized collaborative control, and the integration of low-carbon incentive mechanisms.

1.3. Significance and Objectives of the Study

This study transcends conventional two-dimensional design paradigms by integrating the temporal dimension as a core element into three-dimensional modeling, thereby enriching the design of intelligent transportation devices and establishing an "spatiotemporal integration" framework. The entire process adopts standardized thinking to regulate the structural, functional, and interactive aspects of physical models, filling a theoretical gap in the standardization of intelligent transportation visualization models. Practically, the standardized design process reduces production costs and maintenance complexity, while spatiotemporal visualization enhances data interpretability and scene fidelity, providing a scientifically rigorous and practically applicable physical medium for intelligent transportation experiments. The innovative design approach offers a reference for similar intelligent devices and promotes advancement within the field of intelligent transportation.

The primary design objectives of this study are as follows: first, to develop a three-dimensional (3D) spatiotemporal coordinate system based on visual cognition, enabling dynamic representation of trajectory data in the x-y-t space, with an accuracy of trajectory matching within 1.93 mm, a temporal synchronization error not exceeding 30 ms, and an enhancement of spatiotemporal correlation recognition efficiency by over 40%; second, to adhere to principles of systematization and standardization by completing the comprehensive design and construction of a high-precision physical sandbox measuring 2m×1.5m, encompassing structural layout, device integration, and interface compatibility, facilitating multimodal traffic flow data acquisition; third, to optimize virtual-physical interaction experiences by establishing real-time linkage interfaces between digital twins and physical sandboxes, thereby improving operational convenience and data visualization clarity to meet requirements across experimental and educational scenarios.

2. Theoretical Foundations and Technological Principles

2.1. Theoretical Framework of Spatiotemporal Three-Dimensional Modeling

The core of the design paradigm centers on a user-centric approach that unifies functionality and form. Addressing the traditional spatial-temporal information disjunction inherent in sandbox models, this research introduces the temporal dimension (t) as a fundamental design element, integrating it with spatial coordinates (x, y) to establish a three-dimensional "x-y-t" coordinate system, as illustrated in Figure 1, thereby achieving a cohesive spatiotemporal integrated design representation. This conceptual framework emphasizes the

incorporation of the temporal axis to transform static spatial trajectories into dynamic spatiotemporal curves, facilitating intuitive visualizations of traffic flow evolution. Guided by principles of information transmission, the design employs variations in curve density, color gradients, and tangent orientations to distinctly encode key variables such as vehicle velocity, carbon emissions, and heading angle, thereby enabling multidimensional data visualization with high efficiency. Additionally, the design incorporates a bidirectional mapping between physical and virtual coordinate systems to ensure precise alignment between the digital model and the physical sandbox, fulfilling the functional requirements of "virtual-physical integration."

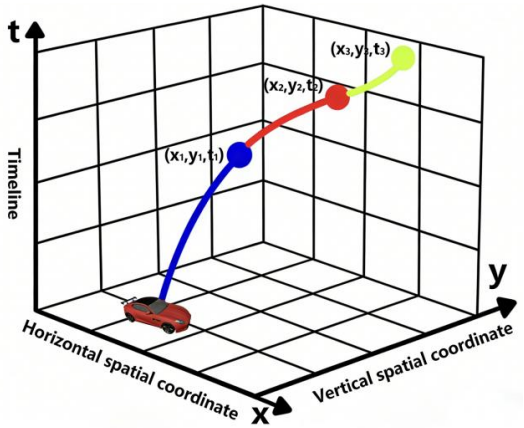


Figure 1. Spatial-temporal coordinate modeling in the x-y-t framework

2.2. Vehicle Dynamics and Kinematic Modeling

To ensure the physical authenticity of trajectory data, kinematic and dynamic vehicle models are incorporated. The vehicle model, depicted in Figure 2, treats the vehicle as a rigid body and characterizes the relationship among pose, velocity, and front wheel steering angle. The primary governing equations are as follows:

$$\begin{cases} \dot{x}=v\cos\varphi \\ \dot{y}=v\sin\varphi \\ \dot{\varphi}=\frac{v\tan\delta}{L} \end{cases} \tag{1}$$

where x and y denote the vehicle's positional coordinates, φ represents the heading angle, v is the vehicle velocity, δ signifies the front wheel steering angle, and L is the wheelbase length. The kinematic model accounts for the vehicle's force interaction, with the longitudinal dynamic equation described as

$$m\dot{v}=F_{trac}-F_{areo}-F_{roll}-F_{grade} \tag{2}$$

Lateral dynamics, characterized by parameters such as tire cornering stiffness and yaw moment, delineate vehicle steering behavior, providing physical constraints for trajectory modeling to ensure that simulated trajectories accurately reflect the physical motion characteristics of the vehicle.

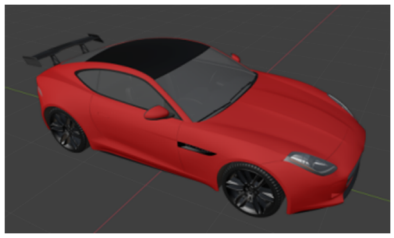


Figure 2. Vehicle Model

2.3. Digital Twin and Edge Computing Technologies

Digital twin technology constructs virtual replicas of physical entities to enable real-time interaction between physical and virtual data and closed-loop optimization; its core lies in establishing state-mapping equations between the physical space and the virtual space:

$$\begin{cases} \dot{X}_v=f(X_p,\theta,t)+\omega(t) \\ Y_P=\mathrm{h}(X_v)+v(t) \end{cases} \tag{3}$$

Here, Xv denotes the state vector of the virtual space, Xv denotes the state vector of the physical space, θ represents the set of simulation parameters, and ωt and vt denote the process noise and observation noise, respectively. Edge computing technology, through the deployment of micro edge nodes such as Raspberry Pi clusters, enables localized real-time processing of traffic data, thereby reducing data transmission latency and providing computational support for real-time decision-making in path optimization. Meanwhile, it supports parallel processing of multimodal traffic flow data, enhancing the overall response efficiency of the system.

3. The Application Value of Traditional Embroidery in Modern Fashion Design

3.1. Digital Twin and Edge Computing Technologies

Guided by information visualization principles, the whole-process design of the "x-y-t" 3D coordinate system is completed. In the spatial axis design, based on the physical dimensions of the 2m×1.5m physical sandbox, a 1:15 scaling ratio is adopted. The origin is set at the bottom-left corner of the sandbox, with the x-axis along the length and the y-axis along the width. Precise axis calibration is completed via UWB positioning equipment, with a design spatial positioning error of, ensuring design precision in spatial dimensions. In the time axis design, the experiment start time is set to, and trajectory times are recorded at a 100Hz sampling frequency. A time synchronization mechanism is designed using GPS timing technology, ensuring a time synchronization error of, achieving precise matching of spatiotemporal dimensions. In trajectory visualization design, collected trajectory data (X_p, y_p, t_p, v_p) is mapped into 3D curves. Data expression is optimized through visual communication principles: velocity information is intuitively presented through curve density design; heading angle is characterized by the tangent direction of the curve; V2X communication status uses color-coding design; and carbon emission levels are distinguished by color intensity. The visualization design of multi-dimensional information makes the transmission of spatiotemporal data more efficient, aligning with the core philosophy of being "people-oriented."

3.2. Standardized Design and Construction of the Physical Sandbox

Following systematic and standardized principles, the whole-process design and construction of the physical sandbox were completed, covering three core design modules: structure, roads, and equipment. The physical object is shown in Figure 3.

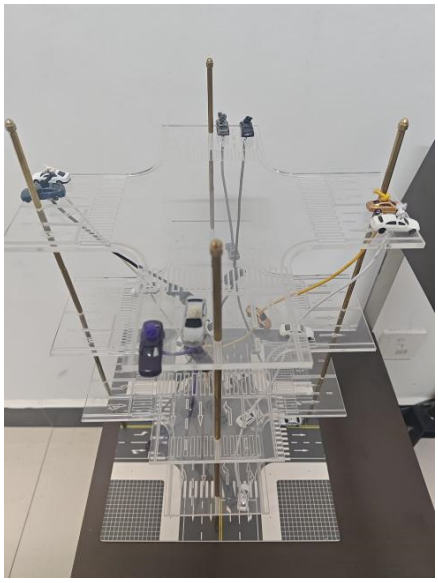


Figure 3. Physical Sandbox Model

3.2.1. Structural Layout Design

The sandbox base adopts a 6061 aluminum alloy profile welded frame, designed with dimensions of 2m × 1.5m × 0.8m, balancing structural stability and lightweight requirements. Table surface flatness error is controlled within to ensure equipment installation precision. An 18mm thick high-density fire-retardant board is paved over the frame as the base surface, with anti-static treatment on the surface to avoid electromagnetic interference.

3.2.2. Road System Design

The road system is fabricated using 3mm thick acrylic sheets. Based on a 1:15 scale, the main road width is designed at 8cm and branch roads at 6cm. Gaps between module joints are, secured by strong adhesive to prevent displacement. Road markings are painted with wear-resistant reflective paint; adhering to visual standards, lane lines are 1cm wide, stop lines are 2cm wide, and crosswalk stripes are 0.8cm wide, with marking position error. At intersections without traffic lights, virtual right-of-way indicators and carbon emission prompt indicators are designed to improve information transmission efficiency and adapt to experimental scenario requirements.

3.2.3. Sensing and Communication Equipment Integration Design

Based on modularity and compatibility principles, the integration design of sensing and communication equipment was completed. The perception layer designs a four-dimensional spatiotemporal data acquisition network, deploying millimeter-wave radar, piezoelectric flow sensors, a UWB positioning grid, and infrared thermal imagers. UWB base stations are arranged at the four corners to ensure dead-zone-free positioning coverage; millimeter-wave radars are deployed at the four corners of intersections with a designed detection range of, providing supplementary data for trajectory modeling; RFID readers are deployed to track non-motorized vehicle trajectories. All sensor interfaces are designed according to industrial standards to improve compatibility. The communication layer designs an integration scheme for V2X communication modules and LoRaWAN transmission units. Roadside units adopt a miniaturized design with pre-set magnetic mounting bases at 33.3cm intervals for easy adjustment later; miniature smart cars are equipped with on-board units supporting real-time V2V and V2I communication. All equipment uniformly uses Type-C power supply and communication interfaces, achieving concealed circuit design through pre-buried trunking, balancing neatness and safety.

4. Design Result Verification and Evaluation

4.1. Modeling Design Precision Verification

According to performance testing standards, the design precision of the "x-y-t" 3D modeling was verified. 20 sets of trajectory data at different vehicle speeds (5~30cm/s) were selected for testing. Results show the mean spatial deviation between the digital model and the physical sandbox trajectory is 1.93mm, with a maximum deviation of, meeting design precision requirements; the mean time synchronization error is 22ms, far lower than the sensor sampling period, ensuring the accuracy of spatiotemporal association. An evaluation group composed of 15 transportation researchers and industrial design professionals was invited to conduct a subjective assessment on two dimensions: information transmission efficiency and visual effect. The results indicate that compared to traditional 2D design, 3D spatiotemporal visualization design shortened the identification time for congestion diffusion events from 12.5s to 7.2s, increasing identification efficiency by 42%; information acquisition accuracy increased from 81% to 94%, and satisfaction with visual effects reached 92%, verifying the effectiveness of integrating the time dimension into the design.

4.2. Physical Sandbox Design Rationality Verification

A multi-dimensional evaluation of the rationality of the physical sandbox design was conducted: regarding structural stability, after 72 hours of continuous operation, the base showed no deformation, and the table surface flatness error remained at. Regarding equipment compatibility, all sensing and communication equipment interfaces adapted well, with no data transmission interruptions observed; V2X communication latency was and packet loss rate. Regarding scalability, the standardized interface design supports the rapid access of new sensors and smart cars, verifying the systematic nature and foresight of the design.

5. Conclusion and Outlook

5.1. Research Conclusion

This study, centered on design thinking, integrated the time dimension as a key innovation point into the design of an intelligent transportation sandbox, completing the construction of an "x-y-t" 3D stereoscopic coordinate system and the standardized construction of a physical sandbox. The main design achievements are as follows: First, established the core innovative concept of "Time Dimension + Industrial Design," breaking through the limitations of traditional 2D design and constructing an "x-y-t" 3D stereoscopic coordinate system. Through visual design language, spatiotemporal data is transformed into intuitive dynamic trajectories, achieving efficient transmission of multi-dimensional information, increasing spatiotemporal association identification efficiency by 42%, reaching a digital-physical trajectory matching accuracy of 1.93mm, and a time synchronization error of , enriching the design methodology of intelligent transportation equipment. Second, completed the whole-process design and construction of the physical sandbox,

adhering to systematic, standardized, and practical design principles, covering multiple dimensions such as structural layout, road systems, and equipment integration. The constructed 2m×1.5m high-precision sandbox achieves precise acquisition and real-time transmission of multi-modal traffic flow data, with a stable structure, convenient operation, and strong compatibility, forming a replicable intelligent transportation sandbox paradigm. Third, optimized virtual-real interaction design, building a real-time linkage platform between the digital twin and the physical sandbox, improving scenario fidelity and operational experience, meeting the needs of multiple scenarios such as experiments and teaching, and providing a successful practical case for the intelligent transportation field.

5.2. Research Limitations and Outlook

The design limitations of this study are: First, extreme weather impacts on sensor performance were not fully considered, lacking corresponding protective designs; second, the personalized customization design of the sandbox is insufficient, making it difficult to quickly adapt to the special needs of different experimental scenarios. Future design optimization directions: First, strengthen environmental adaptability design by adding rain and fog simulation modules and sensor protection structural designs to improve sandbox stability in complex environments. Second, deepen modular and customized design, adopting detachable structural layouts and configurable functional modules to support rapid transformation for different scenarios. Third, optimize the visualization interface and interaction design, incorporating user experience feedback and introducing adaptive interface design to improve operational convenience for different user groups. Fourth, expand the depth of cross-disciplinary integration in industrial design, further integrating low-carbon design concepts into links such as material selection and energy consumption control of the sandbox, promoting the development of intelligent transportation sandboxes towards green and intelligent directions.

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References

[1] Yang Xiangfei, Tong Dongdong, Zhang Jingfang. Resilience Analysis of Urban Rail Transit Networks Based on Complex Networks [J]. China Railway, 2025, (11): 141-150. DOI:10. 19549/ j.issn.1001-683x.2024.10.23.002.

[2] Li Ran, Guo Jinwei, Li Ziyan, et al. Intelligent Traffic Simulation System Based on Multi-Sensor Fusion [J]. Computer Knowledge and Technology, 2022, 18(27): 82-85. DOI: 10.14004/j.cnki.ckt.2022.1775.

[3] Eichler, Stephan. "Performance evaluation of the IEEE 802.11 p WAVE communication standard." 2007 IEEE 66th Vehicular Technology Conference. IEEE, 2007.

[4] Jung, Chanyoung, et al. "V2X-communication-aided autonomous driving: System design and experimental validation." Sensors 20.10 (2020): 2903.

[5] Hegde, Anupama, and Andreas Festag. "Artery-C: An OMNeT++ based discrete event simulation framework for cellular V2X." Proceedings of the 23rd International ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. 2020.

[6] Alnasser, Aljawharah, Hongjian Sun, and **g Jiang. "Cyber security challenges and solutions for V2X communications: A survey." Computer Networks 151 (2019): 52-67.

[7] Wei Wei. Research on Resource Management Technology for D2D/V2X Communication [D]. Beijing University of Posts and Telecommunications, 2017.

[8] Feng Yijia. Research on Trajectory Planning and V2X Transmission Technology for Intelligent Connected Vehicle Platoons [D]. Shanghai Jiao Tong University, 2022. DOI:10. 27307/ d.cnki.gsjtu.2022.000034.

[9] Hu Yanru. Analysis of the Current Status of 5G V2X Communication Applications and Its Sidelink Identifier Update Technology [J]. China Plant Engineering, 2023, (16): 101-102.

[10] Luo Chunli. Optimization Modeling and Energy Consumption Control Based on Traffic Information Collaborative Transmission in V2X Environment [D]. Guangxi Normal University, 2023. DOI:10.27036/d. cnki. ggxsu. 2023. 000913.

[11] Jmaa, Yomna Ben, and David Duvivier. "A review of path planning algorithms." International Conference on Intelligent Systems Design and Applications. Cham: Springer Nature Switzerland, 2023.

[12] Kumar, Neetesh, et al. "Deep reinforcement learning-based traffic light scheduling framework for SDN-enabled smart transportation system." IEEE Transactions on Intelligent Transportation Systems 23.3 (2021): 2411-2421.

[13] Zhou Li Haolin, Hu Minghua, Tian Wen, et al. Research on Traffic Flow Identification in Multi-Airport Terminal Areas Based on Improved Density Clustering Algorithm [J]. Journal of Wuhan University of Technology (Transportation Science & Engineering Edition), 2025, 49(04): 741-748.

[14] Li Zongyang. Design and Implementation of Traffic Safety Monitoring System for Intelligent Connected Vehicles [D]. Beijing Jiaotong University, 2022. DOI:10.26944/ d.cnki. gbfju. 2022.002288.

[15] Ben-Akiva, Moshe, et al. "Traffic simulation with dynamit." Fundamentals of traffic simulation. New York, NY: Springer New York, 2010. 363-398.

[16] Gidlewski, Mirosław, et al. "Sensitivity of a vehicle lane change control system to disturbances and measurement signal errors – Modeling and numerical investigations." Mechanical Systems and Signal Processing 147 (2021): 107081.

[17] Farag, Mohamed MG, and Hesham A. Rakha. "Development and evaluation of a cellular vehicle-to-everything enabled energy-efficient dynamic routing application." Sensors 23.4 (2023): 2314.

[18] Xing Honghong, Xu Ying, Jiang Xuejie, et al. Application of 5G Communication Technology in Intelligent Transportation Systems [J]. Traffic Energy Saving & Environmental Protection, 2023, 19(06): 120-126.

[19] Chen Xusheng, Dai Yong, Wen Chengchao, et al. Unmanned Vehicle Positioning Method Based on Multi-Sensor Fusion [J]. Journal of Shenyang Ligong University, 2025, 44(02): 34-40+47.