Lecture Notes in Electrical Engineering 1390

Limin Jia · Dongxiu Ou · Hui Liu ·
Fang Zong · Pangwei Wang ·
Mingfang Zhang *Editors*

The Proceedings of 2024 International Conference on Artificial Intelligence and Autonomous Transportation

Volume II

Springer

Lecture Notes in Electrical Engineering 1390

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ISSN 1876-1100 ISSN 1876-1119 (electronic)
Lecture Notes in Electrical Engineering
ISBN 978-981-96-3960-1 ISBN 978-981-96-3961-8 (eBook)
https://doi.org/10.1007/978-981-96-3961-8

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Contents

A Framework for Autonomous Transportation Systems: A Case Study on Autonomous Vehicles Following Dynamics Simulation

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Abstract. As emerging technologies advance, Intelligent Transportation Systems (ITS) are transitioning to Autonomous Transportation Systems (ATS). This paper comprehensively outlines and compares the hierarchical mechanisms of ITS across various countries and introduces a theoretical framework for ATS. The framework defines five key elements and their interrelations, proposing a service-oriented hierarchical logical and physical architecture. To validate the ATS theoretical framework, we conduct a case study on autonomous vehicles (AVs) crossing intersections, comparing the efficiency of cloud computing, fixed edge computing, and mobile edge computing. This study captures the scenario architecture through the collaborative relationship of ATS services and conducts traffic flow dynamic simulation. Results indicate that mobile edge computing demonstrates the best performance, enhancing traffic efficiency by approximately 4.9–7.3%. The theoretical framework provides reference for transportation system architects and engineers. Furthermore, this method can be extended to other traffic scenarios, laying the groundwork for practical applications in future industry advancements.

Keywords: Autonomous Transportation Systems · Intelligent Transportation Systems · Framework · Architecture · Autonomous Vehicles Following Dynamic Simulation

1 Introduction

1.1 Connotations of Autonomous Transportation Systems

ITS promote the transport of people and goods by the organic combination of various traffic components with people, vehicles, roads, environment, and information. ITS focus on building efficient, safe, and ecologically friendly transportation systems to ensure the orderly operation and controllability of transportation systems, ITS in China has developed rapidly since the 1990s, and entering a new stage [1], that is characterized by connectivity, collaboration, and smartness, and aims to build a service-oriented

L. Jia et al. (Eds.): AIAT 2024, LNEE 1390, pp. 1–25, 2025.
https://doi.org/10.1007/978-981-96-3961-8_1

transportation operation mode and realize dynamic response to traffic demand. Some scholars in China call this transformative new generation of transportation systems as ATS [2, 3] and divide its development process into three stages: Assisted Autonomous, Highly Autonomous and Fully Autonomous.

ATS could be defined as follows: a development tendency from being passive to being active is happening in the current transportation process, which generates the concept of ATS. ATS is the next generation of ITS that operates in a new way as auto organization and autonomous serving, whose operating mechanism obeys the logic of autonomous perception, autonomous learning, autonomous planning and autonomous action (A-PLPA), that aims to enhance the autonomous ability of transportation systems through reducing human intervention, which is manifested in four aspects including the active response to transportation requirements, automatic operation of vehicles, active control of infrastructure and active adaptation to external environment.

1.2 Framework in Transportation System

System framework is an effective way to describe the new transportation system [4, 5], the architecture with the potential of high performance, maintainability and scalability will effectively guide the construction of ATS [6–8]. As the Edge Computing and Internet of Things technologies develop, the construction of an ATS cyber-physical system is the inevitable trend, whose processes firstly informatize the transportation infrastructure, then connect it to the network system with advanced communication techniques, and finally associate various entity resources in the reference with transportation architecture.

ATS being capable of dealing with random transportation scenarios and realizing the transportation process through serving will be the leading trend in future transportation systems. However, ATS architecture theory has not been reported yet, thus those transportation system architects are unable to start the advanced planning and construction of ATS due to the lack of corresponding guidelines.

In this paper, we aim to develop a basic theoretical framework of ATS and evaluate the effects of ATS architecture on traffic performance through a random traffic scenario. Specifically, first, we summarize the ITS framework from each typical country or region. Then based on the service-oriented architecture (SOA) method, the ATS framework is proposed including five basic elements of service, demand, technology, function, and component, and correspondingly we also elaborate connotations of each element. Besides, to guide the construction of ATS, we build the logical and physical architecture paradigm of ATS service, which could form a fundamental knowledge base for traffic scenario architecture. Finally, dynamic traffic flow simulations are conducted using autonomous vehicles passing through intersections as an example to test the impact of edge computing on traffic operation efficiency. The effectiveness of the ATS theory is validated through comprehensive coverage of scenario services and improvement in traffic performance.

2 Related Work

2.1 US Transportation Framework

The construction of ITS in the United States has always been policy-oriented. US ITS framework was named the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT) and was developed using a process-oriented approach which has been updated to version 9.0. ARC-IT divides a total of 150 transportation service packages into 12 fields according to different service contents and describes each service package from its enterprise view [9], functional view [10, 11], physical view [12] and communication view [13, 14].

2.2 EU Transportation Framework

The European Union launched the KAREN project in 1998, started the development of the European ITS system framework, and completed the design of the logical architecture and the physical architecture in 1999, gradually forming the European ITS framework as the Frame Architecture Made for Europe (FRAME) [15, 16]. The EU expects to establish an open, stable and reliable ITS architecture that provides an integrated and interoperable underlying stable framework for ITS deployment within Europe, which can support multiple ground transportation modes and free switching between different modes while ensuring technical independence. As shown in the Fig. Below, the EU framework is mainly divided into user requirements, logical architecture, physical architecture, communication architecture and technical equipment standards. Based on FRAME, each country can build an ITS architecture that meets its national conditions according to its own needs.

2.3 Japan Transportation Framework

In January 1998, Japan started the development of the national ITS system framework and completed the framework development in January 1999. Regarding the design of the ITS system framework, Japan advocates that: a complete ITS framework ensures collaborative work among various transportation subsystems, and achieves coordination and unity among subsystems, the ITS framework needs to facilitate the expansion of systems and formulate national ITS standards [17]. The most important feature of the Japanese ITS system framework is that it emphasizes the interaction and sharing of ITS information, and the whole ITS construction is a part of social informatization (e-Japan). Japan has adopted the object-oriented method to establish the ITS system framework, which mainly includes three parts: user service, logical framework and physical framework.

2.4 China Transportation Framework

In the 1990s, the Ministry of Science and Technology of China took the lead in launching the second edition of the "China Intelligent Transportation System Framework" [14, 18, 19], which provided effective guidance for the development of ITS in China. The

Chinese ITS system framework adopts a process-oriented research method, which is mainly composed of user subject, service subject, user service, logical frame, physical frame and standards.

A brief comparison of ITS frameworks in various countries is summarized in Table 1. Through the comparison, it becomes evident that traditional ITS theoretical frameworks have certain limitations. Currently, both domestically and internationally, there is a general lack of clear definitions for the underlying elements of transportation systems. There is a deficiency in in-depth analyses of the connotations, interrelationships, and interlocking mechanisms of these elements. This limitation hinders the construction of a comprehensive architecture for transportation systems and fails to provide long-term and holistic guidance for the development of top-level transportation infrastructure. Moreover, most frameworks adopt a process-oriented research approach, which compromises the completeness and expandability of the system architecture. This approach proves challenging for subsequent updates and maintenance. In the context of continuous development in informatization, this methodology is no longer sufficient to meet the evolving demands of transportation development and management. To address these limitations, we undertake research on the ATS theoretical framework. This research aims to overcome the identified shortcomings and results in the development of a foundational framework. This framework is applied in practical scenarios, offering guidance and reference for transportation system architects and engineers. Simultaneously, it lays the groundwork for the implementation of future industry advancements. This aspect represents the innovation and significance of our study.

Table 1. A brief comparison of ITS frameworks in various countries.

Country region	Framework development time	Development methodology	Architecture elements
United States	1992	Process-oriented	Enterprise view, functional view, physical view, communication view
European	1998	Process-oriented	User requirements, logical architecture, physical architecture, communication architecture and technical equipment standards
Japan	1998	Object-oriented	User services, logical framework, physical framework
China	1999	Process-oriented	User subjects, service subjects, user services, logical frameworks, physical frameworks, and standards

3 System Framework of ATS

ATS could be understood as an intelligent agent that offers services to meet the transportation requirements of people and cargo. Therefore, we design 5 basic elements of ATS following the SOA methodology [20, 21], we decouple the capabilities of the transportation system into several independent basic units as the service, summarize the requests and tests for the transportation system as the demands, summarize the factors that promote the capability and evolution of the transportation system as the technology, summarize the units that support the operation of service as the function, and summarize the participating role of the transportation system as the components.

The relations among those elements are described in the Fig. 1. In ATS, the essential role of service is to meet the demand of requirement, which belongs to the concept of transportation business perspective, and the service set represents the capabilities of the current transportation system. The function is used to realize the service, which belongs to the concept of information system perspective. The relations between functions could be further interpreted by logical and physical architecture. Technology is the direct factor that affects the updating and displacement of function, which is also the primary driving factor to the evolution of ATS. A component is positioned at the center in this theory, that generates demands, participates in the process of service and also acts as the role of function carrier, additionally, some connected with physical entities are affected by technology progress [22].

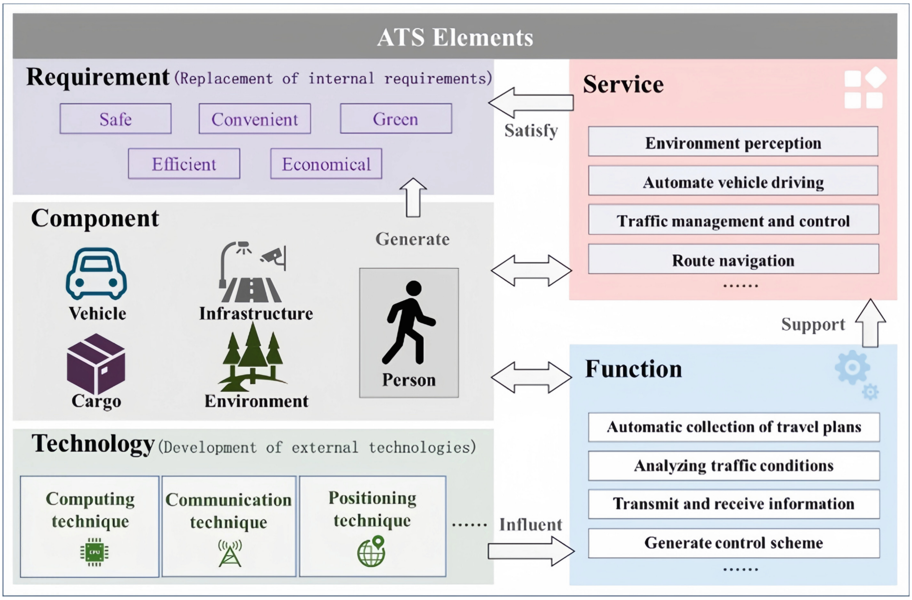

Fig. 1. The association relation diagram of ATS elements.

3.1 ATS Service

Services refer to a class of relatively independent activities generated to meet transportation demand. This study, from the perspective of system users, delineates what the transportation system "should do," encompassing various aspects of transportation services, including travel, management, and planning. Based on the logical relationships among physical elements, information interaction, and policy management, this study divides the overall ATS into 9 service sub-domains (SSD). The logical division of SSD is illustrated in Fig. 2, corresponding to the layers of elements, information, and management. In this context, elements, as entities participating in traffic activities, serve as the main carriers for planning and management. Therefore, there are arrows connecting the element layer and the management layer. Additionally, the autonomous operation of ATS relies on data transmission and information interaction, making the information layer the core component connecting various service domains.

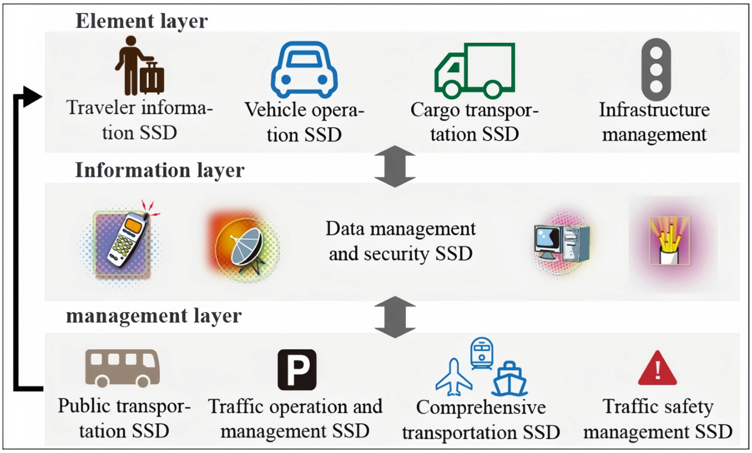

Fig. 2. Schematic diagram of ATS service.

3.2 ATS Demand

The demand generated from traffic participants manifests in 2 aspects. On one hand, it is from the people's willingness and refers to the travel process from origin to destination, which could be understood as the demand. On the other hand, it comes from the interactive conflict with stakeholders, changes of scenarios and updating of functional systems, which could be understood as a requirement. In the ATS, to classify all the demands of traffic participants and verify the completeness of the service set, a demand system model, based on the Theory of Activity [23], is proposed to analyses and deduce the specific demand.

The theory consists of 6 elements, namely subject, object, community, tool, rule and labor division, then it is essential to associate each element in ATS to the theory, as shown in Fig. 3. The traffic initiator is associated with a given subject. The transportation objective is associated with an object. The traffic manager, operator, supplier, maintainer, etc. are associated with a community. The vehicles, automatic driving systems, infrastructure, communication devices, etc. are associated with tools. Traffic laws, policies, standards, etc. are associated with rules. The collaboration way is associated with the labor division. Next in the reference with contradiction analysis rules from the theory, the new demands could be deduced from the combination of subject-object-tool, the combination of subject-community-rule and the combination of object-community-labor division.

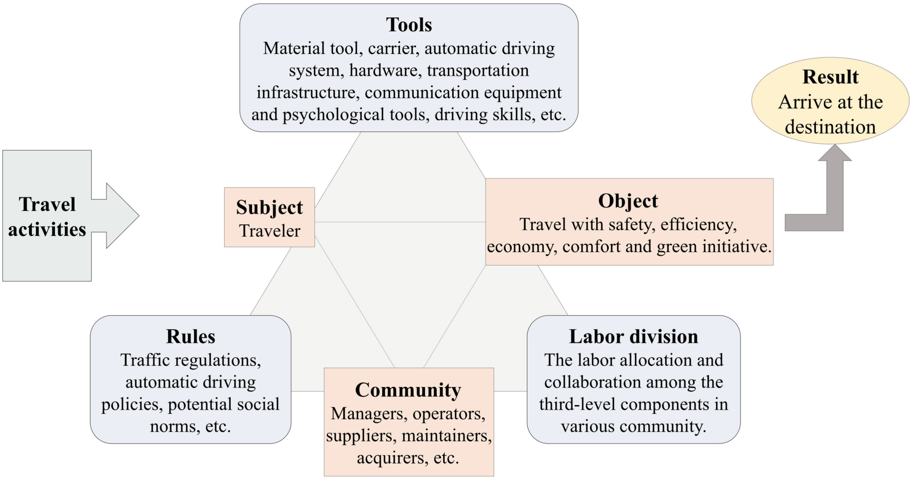

Fig. 3. Schematic diagram of ATS demand.

3.3 ATS Technology

Based on the A-PLPA operation logic, we have summarized the major ICT techniques that support and affect the operation of ATS systems, as shown in Fig. 4. Autonomous perception mainly contains positioning and sensor techniques. Autonomous learning mainly contains big data and computing techniques. Autonomous planning mainly refers to AI technology. Autonomous action mainly refers to control techniques. Finally, supporting technology mainly contains communication and simulation techniques. The effects that technology brings to ATS will be detailed introduced in the next section.

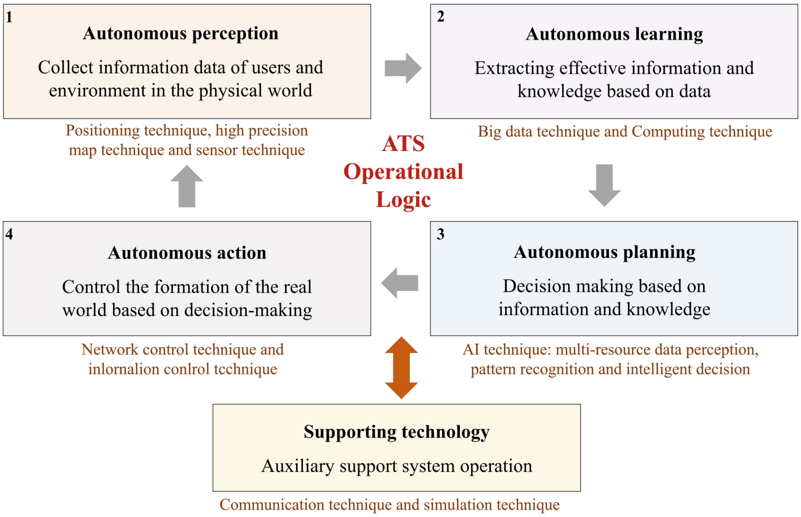

Fig. 4. Schematic diagram of ATS technology.

3.4 ATS Function

In ATS, a function is the basic unit used to realize each service and plays the role of connecting the transportation system and informatization system, whose performance is directly influenced by technologies and that is generally embodied in the traffic participant since it represents a kind of execution capability instead of being an entity [24].

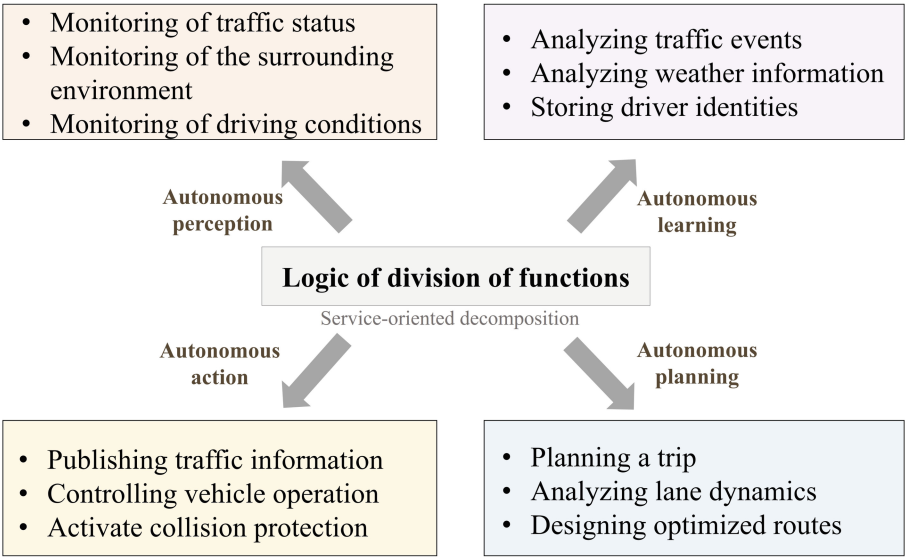

Fig. 5. Schematic diagram of ATS function.

Therefore, when resolving a service with functions, it is the basic way to deduce the system function from the perspective of PLPA, as shown in Fig. 5. To better interpret the content of each function, we have defined the attributes of the function in terms of whom it serves, which traffic participant it is embodied in, what kind of effect it is influenced by technology, etc.

3.5 ATS Component

In ATS, a component is an intermediate role that is a participating role of the service and meanwhile is a carrier of the function. To systematically sort out all the components in ATS, it is classified from 5 aspects, namely user, vehicle, infrastructure, cargo and intelligent device, and further achieves two-level hierarchical classification following the standard of ISO42010, as shown in Fig. 6. In this component framework tree, the first, second, and third-level components are all common components, but they are subdivided at each level with different granularity, ensuring the completeness of the framework. In practical scenarios, these components can carry various services and functions, transmit information flows, and further instantiate into a traffic entity, supporting the operation of the architecture.

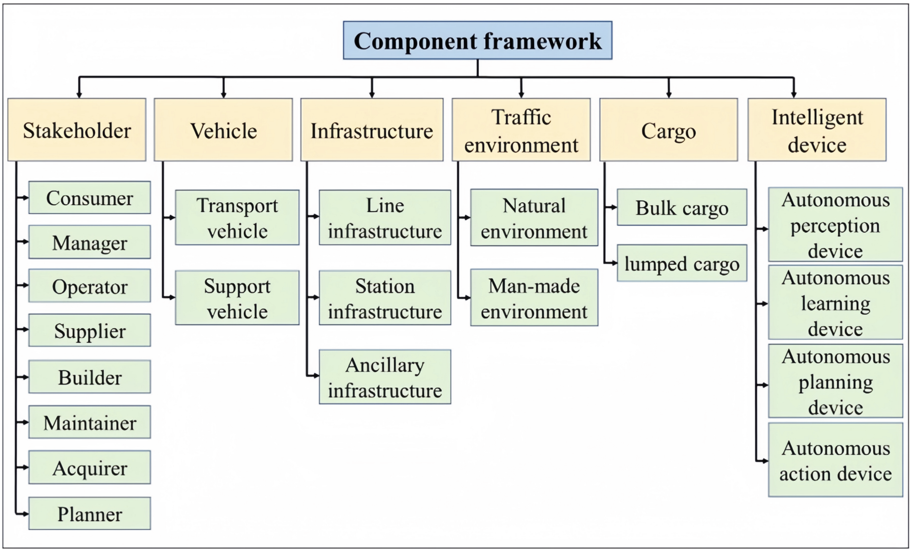

Fig. 6. Schematic diagram of ATS component.

3.6 ATS Logical and Physical Architecture

To better describe the relations among the functions and guide the construction of infrastructure, it is indispensable to build the logical architecture and physical architecture for each service [25, 26]. The construction paradigms for both types of architectures will be explained and the schematic diagram is shown in Fig. 7.

The logical architecture (LA) is realized by way of organizing those informatization functions based on understanding the traffic semantics of each service, which achieves the goal of connecting traffic and system function. The specific effect manifests in two aspects. On one hand, it expresses the hierarchical relations among functions that are furthering the explicit expression of PLPA and thus offers the theoretical basis to the architecture restructuring, fusion, and optimization for any scenarios. Specifically, the perception tier is layered into acquisition and recognition, the learning tier is layered into fusion and analysis, the planning tier is layered into plan generation and optimal scheme selection, and the action tier is layered into execution and feedback. On the other hand, LA also clarifies the input and output of each function in service, thus showing the realization process of service.

The physical architecture (PA) works when LA is applied to the traffic entities, which is the framework view that instructs the planning and construction of transportation systems and also is the ultimate implementation form of ATS theory [27, 28]. Therefore, it is indispensable to connect the system function to the realistic traffic entity. Based on the current construction situation of the transportation system, a theoretical model of "physical object" (PO) is proposed that three types of entity objects namely system, module and individual are designed about cloud-edge-terminal structure. PO describes the properties from its ontology attribute and connection attribute. The former includes object

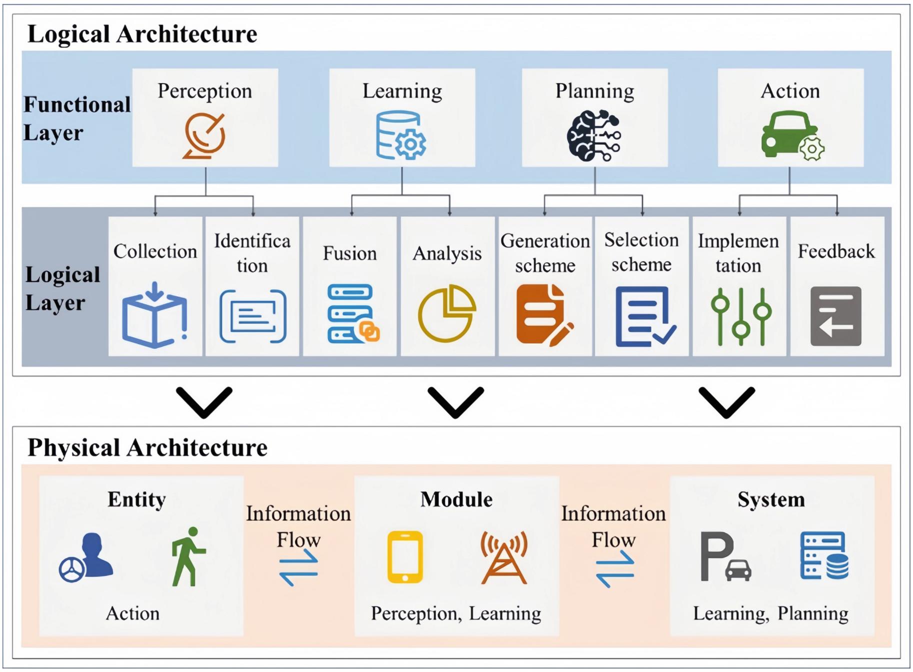

Fig. 7. Schematic diagram of logic and physical architecture in ATS.

category, autonomous capability, and operation way in the information transmission process, while the latter includes access capability and operation logic.

The architecture described above is service-oriented. By identifying the services in a given scenario, along with their timing relationships and implementation logic, the overall architecture for that scenario can be fused and constructed.

4 A Case Study on ATS Scenario

The emergence of edge computing technology, driven by the deployment of 5G and Internet of Things devices, addresses challenges related to data volume, latency, and security [29]. Edge computing processes and analyses data near its source, offering benefits such as faster insights, improved response times, and enhanced bandwidth availability within the 5G network architecture [30]. In the context of ATS, edge computing plays a pivotal role in enhancing the "perception, learning, planning, and action" processes. Utilizing fixed and mobile edge nodes, it broadens traffic data perception and collection, enhancing data integrity and reliability [31, 32]. By offloading computing tasks to edge nodes, it reduces cloud burden, cuts latency, and boosts real-time performance in transportation systems.

However, existing research predominantly focuses on applying edge computing to vehicle operations and communication [33, 34], and simulation outcomes are typically presented in the form of simulators [35, 36]. This overlooks the key indicators of common traffic scenarios affected by edge computing and the broader impact on macro-traffic architecture. Additionally, current studies on transportation frameworks mainly concentrate on the theoretical level, lacking attempts and applications in practical scenarios. To address this gap and validate the usability and effectiveness of the ATS theoretical framework, we design a typical traffic scenario based on ATS basic theory and edge computing technology. Dynamic simulations of traffic flow are conducted using traffic simulation software and car following model, and the intersection capacity and efficiency of ATS under this scenario are analyzed based on traffic metrics.

4.1 Intersection Scenario Description

(1) **Basic Overview**. The intersection of the scenario design is a two-way six-lane crossroads, divided into four directions, where the inlet lane of each direction consists of three lanes of left turn, straight ahead and right turn, and each lane of the intersection area is 100 meters (m). The intersection adopts a fixed phase for signal control, the traffic flow in all four directions is approximately the same, and the types of vehicles driving are all cars or cabs, they can perceive data and communicate between vehicles and roads. This scenario does not consider the impact of pedestrians crossing the street.

(2) **Operation Logic**. After the vehicle enters the intersection, it needs to collect information about the surrounding vehicles and environment in real-time and transmit the sensory data to the data processing facility with the help of communication facilities. After processing the data, the data processing facility generates the action plan of the vehicle according to the actual situation and transmits it back to the vehicle itself.

The vehicle controls itself with the on-board control facility according to the action plan and takes safe and effective action to pass the intersection.

(3) **Scenario Elements**. Building on the concept framework of ATS, we further analyses the five elements in the intersection scenario. Here, technology corresponds to edge computing technology, components correspond to roads and road-testing devices, requirements correspond to the swift passage of vehicles through the intersection, services correspond to road environment recognition, and functions correspond to the storage, import, and analysis of environmental information. According to the three development stages of ATS edge computing technology, technology elements are combined with specific technologies. Specifically, the technology for the Assisted Autonomy stage corresponds to cloud computing technology, for the Highly Autonomous stage corresponds to Fixed Edge computing technology, and for the Fully Autonomous stage corresponds to Mobile Edge computing technology. The detailed technology development roadmap is illustrated in Fig. 8.

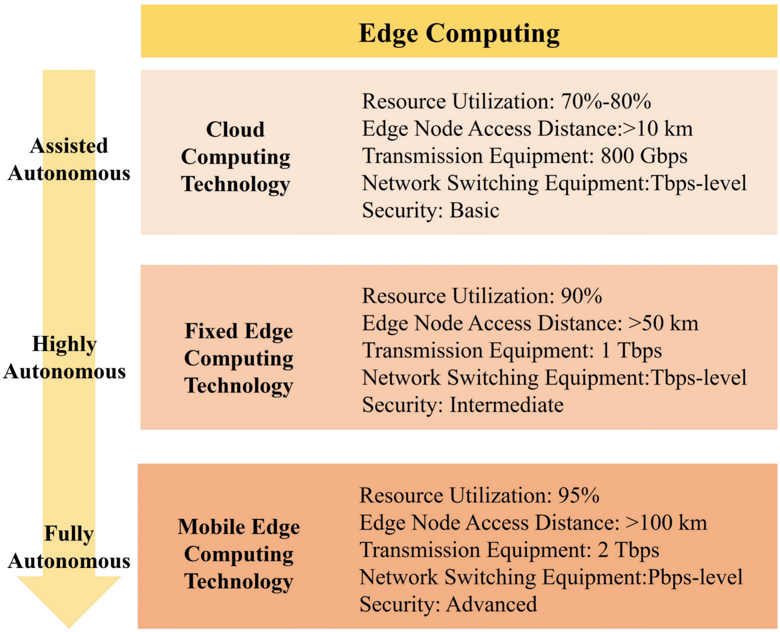

Fig. 8. Development roadmap of edge computing technology.

4.2 Intersection Architecture

The scenario is categorized into three types of intersections based on the data processing facilities and vehicle travel scheme decision facilities. Among these intersections, the cloud computing intersection involves processing on the cloud platform after the vehicle senses various data [37–39]. In contrast, the fixed edge Computing intersection processes data through the edge node located at the intersection after the vehicle senses diverse data [40, 41]. The mobile edge Computing intersection, on the other hand, relies on processing by the mobile edge computing equipment within the vehicle [42, 43]. This enables the design of the temporal relationships for implementing intersection services. Subsequently, distinct physical architectures can be constructed for each of the three intersection types, providing further guidance for setting simulation parameters.

(1) **Intersection Service Logic**. According to the scenario description of automatic vehicles driving through the intersection by ATS, and in combination with the actual situation of the intersection, the service implementation timing relationship and operation logic of the intersection are designed. As shown in Fig. 9.
(2) **Intersection Physical Architecture**. The physical architecture of the three types of intersections in the scenario is derived by merging the physical architectures of the services shown in Fig. 9, which includes ten physical objects and several information

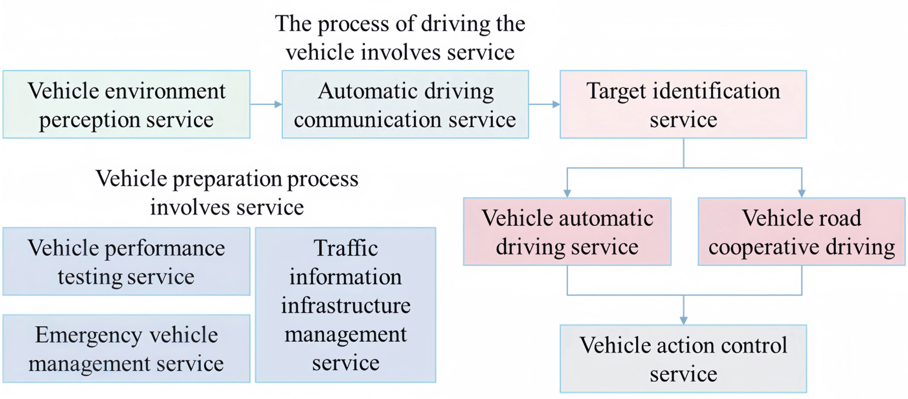

Fig. 9. Service logic for vehicles passing through intersections.

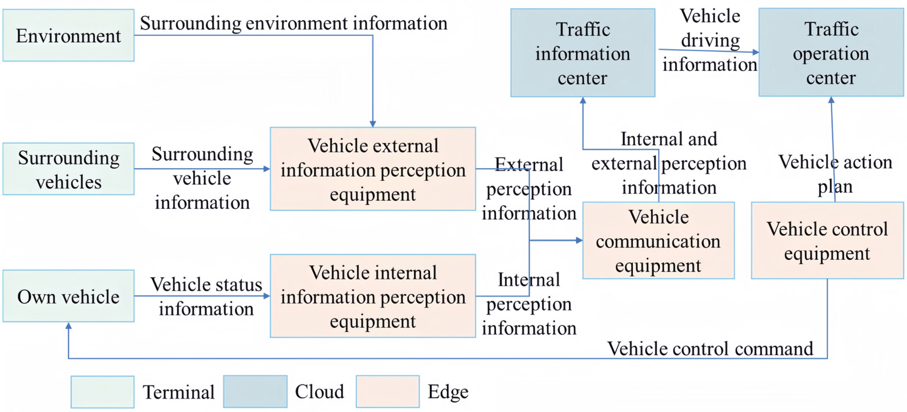

Fig. 10. Physical architecture of cloud computing intersection.

flows. The fundamental distinction among the three types of intersections lies in the varied application and analysis facilities and methods for sensing data.

The physical architecture of cloud intersection, fixed edge Computing intersection, and mobile edge Computing intersection are shown in Figs. 10, 11, and 12. According to the physical architecture, the operational logic and feature settings of three types of intersections can be distinguished, as shown in Table 2.

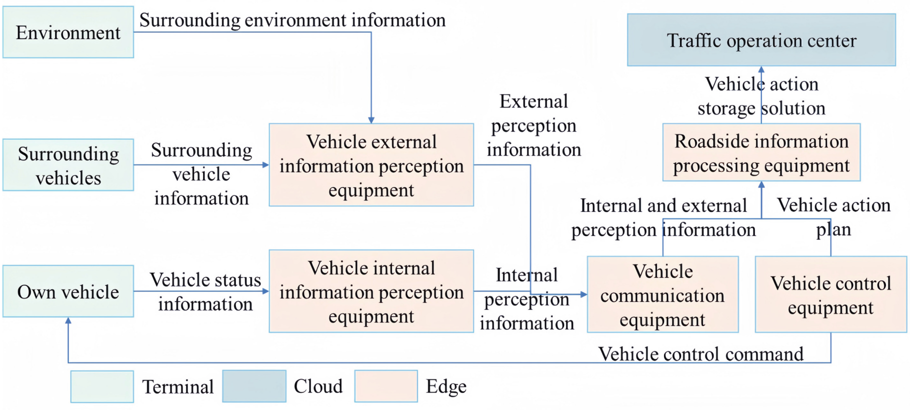

Fig. 11. Physical architecture of fixed edge computing intersection.

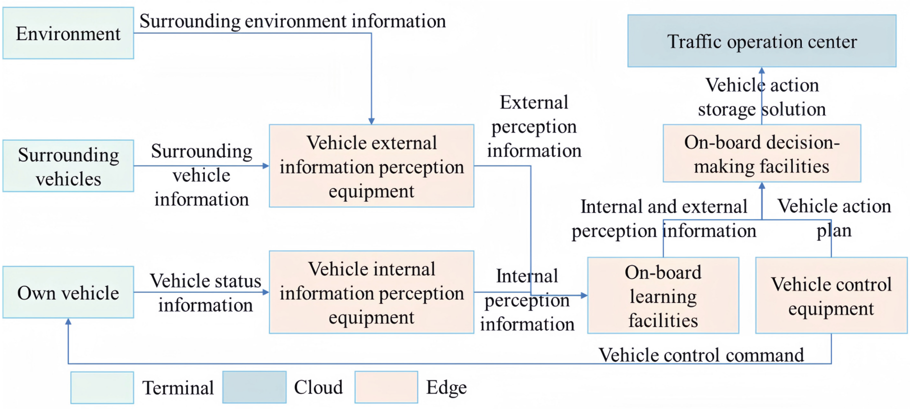

Fig. 12. Physical architecture of mobile edge computing intersection.

Table 2. Specifications in three types of intersections.

Intersection type	Data processing method	Calculate facility location	Computing features	Total delay
Cloud Computing Intersection	Cloud Computing	Intersection Road Network Center	Large computational volume, centralized computational resources, and delays in distributing computational resources	2*(transmission delay + propagation delay) + data processing delay + queuing delay
Fixed edge Computing intersection	Combining Edge Computing and Cloud Computing	Near the intersection	Responsible for the computation of a single intersection, with less latency due to computational resource distribution processing	2*transmission delay + data processing delay + queuing delay
Mobile edge Computing	Combining Edge Computing and Cloud Computing	Carried with the vehicle	Responsible for the calculation of its vehicles, computing resources do not need to be distributed, responsive and good real-time	Data processing delay + queuing delay

4.3 Dynamic Simulation

(1) **Experimental settings**. The simulation scenario under the intersection is built by using SUMO software [44, 45], as shown in Fig. 13.

Table 3 lists the training time, simulation steps, and intersection traffic for the experiments. In addition, the experimental platform is a personal computer with AMD Ryzen 7 4800H CPU @2.9GHz/RAM: 16.00GB, using Python 3.6 and tensorflow1.10.0 to conduct the experiments. The experimental parameter settings are shown in Table 4.

(2) **Model Impact Factors and Evaluation Indicators**. The main factors affecting the

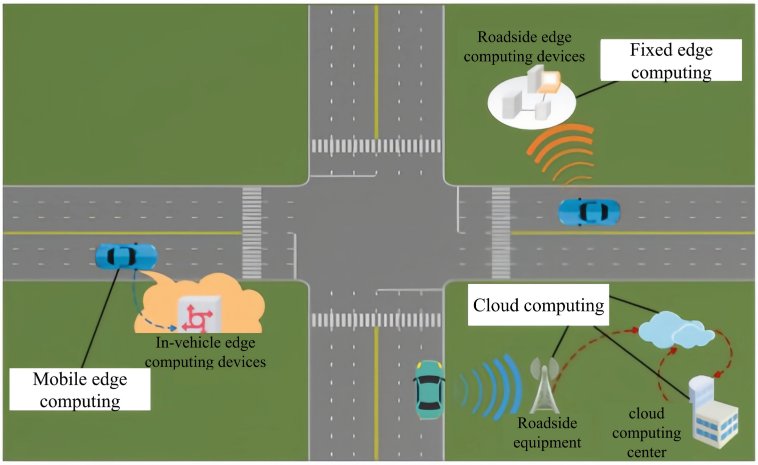

Fig. 13. Simulation scene intersection map.

Table 3. The specifications in three types of intersections.

Application scenarios	Training time (s)	Simulation step (s)	Traffic flow
Cloud computing	2000	0.01	500 in all four directions
Fixed edge computing	2000	0.01	500 in all four directions
Mobile edge computing	2000	0.01	500 in all four directions

Table 4. Parameter setting of the model.

Parameters	Values	Descriptions
Length	5	Vehicle length (m)
Accel	2.6	Vehicle acceleration (m/s^2)
Decel	4.5	Vehicle deceleration (m/s^2)
Min gap	2.5	Distance from front vehicle (m)
Car follow model	Krauss	Model for car following
Action step length	0.01	Length of interval between vehicles
Emergency Decel	9	Maximum deceleration of vehicle (m/s^2)

vehicle following the model of urban roads are road network structure, traffic signal control and individual vehicle behavior. To highlight the three application scenarios, we set the road network structure and traffic signal control as the same to study the impact of edge computing on vehicle driving behavior.

Also, to verify the validity of the experiment, four main metrics were used to evaluate the intersection's traffic conditions, as shown in Table 5, including queue length, waiting time, fuel consumption and occupancy rate of lanes at the intersection.

Table 5. Model evaluation index.

Symbol	Evaluating indicator	Indicator description	Equation
Q	Queue length	Characterizes the maximum value of vehicles waiting to be queued at a given point in time	$\sum_{l=1}^{N_s} q(s)$
W	Waiting time	Characterize the waiting time of vehicles at a given point in time due to queuing at intersections	$\sum_{i=1}^{N_t} w(t)$
F	Fuel consumption	Characterizes the amount of fuel consumed by the vehicle during the journey	$\sum_{j=1}^{N_L} f(L)$
O	Occupancy rate	Characterize the occupancy of the road under the intersection	$\sum_{l=1}^{N} \frac{T}{C}$

In Table 5, l is the number of lanes, N_s is the number of lanes at the intersection, and $q(s)$ is the queue length under the entire intersection. i is the number of vehicles in the queue at the intersection, N_t is the number of vehicles in the queue at the entire intersection, and $w(t)$ is the overall vehicle waiting time at the entire intersection. j is the number of vehicles passing through the intersection, N_L is the number of vehicles passing under the entire intersection, and $f(L)$ is the fuel consumption of the vehicle for the entire trip. N is the number of lanes at the intersection, T is the current traffic volume of the lane, and C is the designed traffic volume of the lane.

(3) **Car Following Model**. Car following model is a dynamic method used to study the influence of the movement state of the leader on the corresponding behavior of the follower [46]. By analyzing the following behavior of each vehicle, the traffic flow characteristics of a single lane are understood, and the traffic capacity and traffic simulation are studied. In the three application scenarios, this paper hopes to process the environmental information of the vehicle through the edge computing device, give the corresponding recommended speed, and compare the application scenarios by influencing the driver to adjust the vehicle speed. Therefore, the car following model selected in this paper is the Krauss model, which is a safe distance model [29, 47]. Assume that the distance between the front car (leader) and the back car (follower) is:

$$g = x_l - x_f - l \tag{1}$$

where l is the length of the vehicle, x_l is the position of the front car, and x_f is the position of the rear car. If the rear car (follower) is required not to collide with the front car (leader) even if it brakes sharply, it is necessary to satisfy

$$L\left(v_f\right) + v_f \cdot \tau < L(v_l) + g \tag{2}$$

where v_f is the speed of the rear car, which is the value to be calculated. v_l is the speed of the front car. $L(v_l)$ is the braking distance of the rear car. $L(v_l)$ is the braking distance of the front car. g is the distance between the cars mentioned above. In general, τ represents the driver's reaction time. In this model, our research subject is AVs, so it is defined as the total delay under different communication modes.

To calculate v_f, it is necessary to give the functional expression of speed $L(v_f)$ and braking distance $L(v_l)$. The Taylor expansion of the function $L(\cdot)$ at $\overline{v} = (v_f + v_l)/2$ is used to replace the function $L(\cdot)$, and the higher-order terms are ignored

$$L'(\overline{v})v_f + v_f \cdot \tau < L'(\overline{v})v_l + g \tag{3}$$

In calculating $L'(\overline{v})$, assuming a deceleration rate of $\dot{v} = -b(v)$ when braking, we have

$$L'(\overline{v}) = \frac{d}{dx} \int_0^v \frac{s}{-b(s)} ds = \frac{v}{b(v)} \tag{4}$$

The integral term of Eq. 4 corresponds to the braking distance when the deceleration is $-b(v)$ during braking. Through Eq. 3 and Eq. 4, we can get

$$v_f < v_l + \frac{g - v_l \cdot \tau}{\frac{\overline{v}}{b(\overline{v})} + \tau} \tag{5}$$

Because $\overline{v} = (v_f + v_l)/2$, and the maximum deceleration of the vehicle is $-b$, so Eq. 5 is organized as

$$v_f < -b\tau + \sqrt{(b\tau)^2 + (v_l)^2 + 2bg} \tag{6}$$

The calculation of the right part of Eq. 6 is the maximum safety speed, recorded as v_{safe}, but also needs to ensure that the vehicle speed does not exceed the maximum speed allowed, to take the safety speed and allow the maximum speed of the smaller value, that is

$$v_f = \min[v_{max}, v(t) + a\Delta t, v_{safe}(t)] \tag{7}$$

Each car will not necessarily drive according to the above speed because of its performance, driving style and other factors, and can take a smaller value, so the introduction of random factor $\epsilon \in [0, 1]$ (imperfection parameter)

$$v = \max[0, v_f - random(0, \epsilon a)] \tag{8}$$

4.4 Experiment and Analysis

(1) **Experimental Procedure**. Based on the physical architecture of the scenario, t can be seen that after sensing data, it needs to be transmitted to data processing facilities, where the data is processed and then transmitted back to the vehicle for behavioral

decision-making. Combining the information in Table 2, the time required for this process is:

$$\tau = 2 \times (D_t + D_s) + D_p + D_q \tag{9}$$

where D_t is the transmission delay, D_s is the propagation delay, D_p is the data processing delay, D_q is the queuing delay.

Assuming that the data size A perceived by the vehicle is 0.25 meters/second (m/s), and the data transmission rate V_t of DSRC technology is 12 mb/s, the transmission delay D_t is: $A/V_t = 0.25/12 = 0.02$ s. Assume that the physical distance between the cloud computing platform and the intersection s is 100 km, and the data transmission rate is based on optical fibre transmission, $V_h = 2 \times 10^8$ m/s, then the propagation delay D_s is: $S/V_h = 100/200000 = 0.0005$ s. The data processing delay D_p is determined by the software and hardware capabilities of the processing facilities, and is set to 0.1 second(s) here. Cloud computing methods will consume a lot of energy. According to the actual investigation, the on-board sensing data transmission delay of cloud computing intersections is about 0.02 s, the propagation delay is about 0.0005 s, and the queuing delay D_q is set here as about 0.5 s, and the data processing delay is about 0.1 s, so the total delay is about 0.64 s.

Because the intersection with fixed edge nodes is close to the vehicle, the propagation delay can be ignored, and the queuing delay is also low. Here, it is set to be about 0.1 s, and the total delay is calculated to be about 0.24 s. The data propagation delay and queuing delay of mobile edge Computing intersection are short and can be ignored. After calculation, the total delay is about 0.1 s After the latency parameter is determined, experiments can be conducted about the process as defined in Algorithm 1.

Algorithm 1 Car following model combined with edge calculation process

Input: Epoch M, Total Delay τ.

Output: Q and W at the intersection at any time within the $2000\ s$. F of the whole journey of the vehicle within $2000\ s$. O of the vehicle on the road.

Initialization: $Q \leftarrow \emptyset$, $W \leftarrow \emptyset$, $F \leftarrow \emptyset$, and $O \leftarrow \emptyset$.

1: **for** step= 1 to M **do**
2: Get the initial environment state;
3: Select an initial vehicle speed by a random factor of ϵ;
4: Get the position of the car in front $x_l$and the speed of the car in front v_l;
5: Transfer position and speed information to edge computing devices;
6: Edge computing device pass-through $v_{safe} < -b\tau + \sqrt{(b\tau)^2 + (v_l)^2 + 2bg}$ calculate recommended speed;
7: Transmit the recommended speed v_{safe} to AVs for speed guidance control;
8: Perform speed setting action in SUMO and observe vehicle deceleration, collision, and environmental status $st + 1$;
9: Updated rear vehicle speed v_f;
10: **end for**

(2) **Result Analysis**. In the experiments, the purpose is to increase the speed of vehicles passing through the intersection as much as possible and improve the traffic efficiency of the intersection under the condition of avoiding vehicle collisions or traffic accidents. The traffic efficiency of intersections in the three cases is compared through the four evaluation indicators mentioned above, as shown in Table 6.

Table 6. Comparison of evaluation indicators in three cases.

Application scenarios	Queue length	Waiting time	Fuel consumption	Occupancy rate
Cloud computing intersection	19.62	324.08	40.15	0.72
Cloud computing intersection	18.56	305.64	39.52	0.67
Mobile edge computing intersection	18.03	296.30	38.96	0.65

It can be seen from Table 6 that the data of mobile edge Computing intersection under the four evaluation indicators are better than that of fixed edge Computing intersection and traditional intersection. However, there is no significant difference between the evaluation indicators of fixed edge Computing intersections and traditional intersections, because the data processing delay is the same, while the traditional intersections only have more queuing delay. The traditional intersection needs to upload cloud and cloud computing, which takes more time, and the efficiency of passing through the intersection is relatively low. The results show that with the cloud computing and edge computing approaches, the improvement is about 5.40–8.10% for the queue length indicator, 5.69–8.57% for the waiting time indicator, and less for the fuel consumption indicator, 1.57–2.96%, and 6.94–9.72% for road occupancy rate indicator. The overall improvement of intersection traffic efficiency is about 4.9–7.3%.

Figures 14, 15, 16, and 17 illustrate a comparison of queue length, waiting time, fuel consumption and lane occupancy rate at traditional intersections, fixed edge Computing intersections and mobile edge Computing intersections under the traffic condition of normal traffic flow.

As can be seen from Figs. 14 and 15, there are no abnormal values in the three cases under the indicators of queue length and waiting time, which are within the normal range. The mean and median of the moving edge method are lower than those of the other two cases, which shows that the queue length and waiting time of this method are better than those of other methods. The overall queue length is between 0–40, indicating the sum of the queue lengths of vehicles on the four roads. The waiting time index is between 100–500, indicating the total waiting time of vehicles at the whole intersection. The height of the box in the three cases of queue length and waiting time is roughly the same, indicating that the fluctuation of the two index data is small at the same time. The