sensors

MDPI

Article

Information System Model and Key Technologies of High-Definition Maps in Autonomous Driving Scenarios

Zhiqi Qian, Zhirui Ye and Xiaomeng Shi *

School of Transportation, Southeast University, 35 Jinxianghe Road, Nanjing 210018, China
* Correspondence: shixiaomeng2020@sina.cn

Abstract: Background: High-definition maps can provide necessary prior data for autonomous driving, as well as the corresponding beyond-line-of-sight perception, verification and positioning, dynamic planning, and decision control. It is a necessary element to achieve L4/L5 unmanned driving at the current stage. However, currently, high-definition maps still have problems such as a large amount of data, a lot of data redundancy, and weak data correlation, which make autonomous driving fall into difficulties such as high data query difficulty and low timeliness. In order to optimize the data quality of high-definition maps, enhance the degree of data correlation, and ensure that they better assist vehicles in safe driving and efficient passage in the autonomous driving scenario, it is necessary to clarify the information system thinking of high-definition maps, propose a complete and accurate model, determine the content and functions of each level of the model, and continuously improve the information system model. **Objective:** The study aimed to put forward a complete and accurate high-definition map information system model and elaborate in detail the content and functions of each component in the data logic structure of the system model. **Methods:** Through research methods such as the modeling method and literature research method, we studied the high-definition map information system model in the autonomous driving scenario and explored the key technologies therein. **Results:** We put forward a four-layer integrated high-definition map information system model, elaborated in detail the content and functions of each component (map, road, vehicle, and user) in the data logic structure of the model, and also elaborated on the mechanism of the combined information of each level of the model to provide services in perception, positioning, decision making, and control for autonomous driving vehicles. This article also discussed two key technologies that can support autonomous driving vehicles to complete path planning, navigation decision making, and vehicle control in different autonomous driving scenarios. **Conclusions:** The four-layer integrated high-definition map information model proposed by this research institute has certain application feasibility and can provide references for the standardized production of high-definition maps, the unification of information interaction relationships, and the standardization of map data associations.

Keywords: autonomous driving; high-definition map; system model; key technology

Citation: Qian, Z.; Ye, Z.; Shi, X. Information System Model and Key Technologies of High-Definition Maps in Autonomous Driving Scenarios. *Sensors* **2024**, *24*, 4115. https://doi.org/10.3390/s24134115

Academic Editor: Felipe Jiménez

Received: 7 May 2024
Revised: 16 June 2024
Accepted: 17 June 2024
Published: 25 June 2024

1. Introduction

High-definition maps are electronic maps with absolute accuracy of up to the centimeter level, which can provide rich static and dynamic traffic information. They are important guarantees for the safe and efficient travel of autonomous vehicles and can provide accurate positioning, optimized routing, and vehicle control for autonomous vehicles [1]. The higher the autonomous driving level, the higher the requirements for high-definition maps (Table 1). Starting from level L3 autonomous driving, the subject of real-time environmental perception has changed from human drivers to autonomous driving systems [2].

Table 1. Rank of autonomous driving.

Rank	Level of Automation	Map Accuracy Requirements (m)	Subject of Environmental Monitoring
L0	Completely driven by humans	10	Humans
L1	Single-function assistance, such as adaptive cruise control	10	Humans
L2	Combined function assistance, such as lane-keeping assist	1–5	Humans
L3	Automatic driving in specific environments, requiring driver intervention	0.2–0.5	System
L4	Automatic driving in specific environments, no driver intervention required	0.05–0.2	System
L5	Full automatic control of the vehicle	0.05–0.2	System

Compared with traditional maps, high-definition maps have the characteristics of high accuracy, strong timeliness, large amounts of data, and high dynamics; can provide more accurate positioning services, more abundant traffic information, more reasonable route planning, and other services; and play an important directing role in the scenario of autonomous driving [3]. With the continuous development of intelligent driving, users' demands for the richness of high-definition map road environment information, the timeliness of information transmission, and the personalization of information are becoming increasingly strong. However, currently, high-precision maps still have problems such as large amounts of data, serious data redundancy, and weak data association, which make autonomous driving vehicles fall into difficulties such as difficult data query and low data transmission timeliness [4], which are not conducive to the efficient control and timely communication of autonomous driving vehicles and further make it difficult to improve user satisfaction. In response to these problems, a large number of experts and scholars have made efforts, especially in the aspect of autonomous vehicle control and communication technology. For example, MA et al. [5] proposed a human–machine shared steering controller based on the Nash game strategy and designed a continuous weight adjustment algorithm to balance the steering control rights of the driver and the intelligent system, significantly improving the vehicle control rights coordination degree and the vehicle path tracking accuracy, which is of great significance for improving the dynamic positioning accuracy of autonomous driving vehicles. Sun et al. [6] proposed a state-aware event-triggered communication strategy, which can dynamically adjust the coupling of vehicle control and communication transmission, which is of great significance for optimizing information transmission. Ding et al. [7] proposed a vehicle control method of human–machine collaborative predictive steering control, which has dynamic path planning and tracking functions and improves the human–machine collaborative steering performance. Using pre-stored data for trajectory prediction is of great importance for avoiding the risks caused by low timeliness of data transmission. Ding et al. [8] took a hybrid heavy-duty truck as the experimental object and designed a steering control system based on the safe elastic trigger output feedback LKC (lane-keeping control) to counter the aperiodic energy-bounded DoS (denial-of-service) attack, greatly reducing the driver's steering burden and the conflict of driving control rights. It also proposed a communication scheme based on the safety and adaptive adjustment of auxiliary variables, which can greatly save information transmission resources and is of great significance for improving the timeliness of information transmission. The emergence of these achievements has a mitigating effect on problems such as difficult data query and low data transmission timeliness of autonomous driving vehicles, but it still needs the support of a complete and accurate high-definition map information system to provide a guarantee for the enrichment of map data information, the optimization of data quality, and the improvement of the degree of data association [9]. In this regard, it is necessary to explore a complete and accurate high-definition map information system model in the autonomous driving scenario and simultaneously analyze the role played by data at different levels of the model in the autonomous driving scenario so as to provide assistance for the development of high-definition maps in coordination with intelligent driving.

2. High-Definition Map Information System Model (HDMISM)

According to the Kolacny theory in the cartography theory, the traditional map information transmission model mainly includes the cartographers (H_1), the map users (H_2), the objective world (W), the cartographers' spatial environment cognitions (C_1), the map users' spatial environment cognitions (C_2), and the map (M_1), that is, $Model_1 = (H_1, H_2, C_1, C_2, W, M_1)$. This theory points out that the traditional map information transmission mainly follows the basic principle of one-way transmission, that is, $W \rightarrow H_1 \rightarrow C_1 \rightarrow M_1 \rightarrow C_2 \rightarrow H_2$. The objective world is recognized by the cartographers and forms the cognition of the world's spatial environment. The cartographers then use a certain map language to create the map based on their own cognition, and the map users parse the map language to further form the cognition of the spatial environment of the objective world [10]. However, the cognitions are mainly based on the cartographers' cognitions of the objective world, and the entire information transmission process follows the principle of one-way transmission, with a clear division between the cartographers and the map users. The information transmitted by the traditional map information transmission model mainly consists of relatively static spatial cognition with low timeliness, which fails to convey dynamic real-time environmental cognition in a timely manner. This is not conducive to the real-time cognition of the dynamic environment by automatic driving vehicles and the making of driving decisions and requires the support of high-definition maps with stronger real-time performance.

This article believes that high-definition maps are more intelligent than traditional maps and that the content included in the information transmission model is richer. For example, both the cartographers and the map users need to not only cognize the geographic spatial environment but also form cognitions of the spatiotemporal environment and complete the perception with a large number of sensors, making the cognitions of the cartographers and the map users dynamic (C_1', C_2'). In addition, it is necessary to add the personalized demand information and cognitive characteristics of the map users (D) so that the high-definition map (M_2) can meet the needs of the map user in real time and have self-adaptability. It should be noted that there is no clear identity boundary between the cartographers and the map users of the high-definition map, and, in certain cases, the identities of the two overlap, and some map users will participate in the map production. As a result, the information transmission model of the high-definition map is $Model_2 = (H_1, H_2, C_1', C_2', W, M_2, D)$. Under this kind of information transmission model, the transmission of information mainly includes six stages: ① Based on D, a user model is built to lay the foundation for leading the cartographers to produce maps that meet the requirements; ② the cartographers obtain information about the objective world and form a cognition (C_1'); ③ the cartographers process the information and form the map M; ④ the map users interpret the map information and form cognitions (C_2'); ⑤ there is interactive feedback between the cartographers and the map users to provide guidance for optimizing the personalized service functions of the map; and ⑥ the cognitions of the map users guide the implementation of their actions. The information transmission model of high-definition maps can be described as shown in Figure 1.

As shown in Figure 1, compared with the traditional Kolacny map information transmission model, the information transmission model of high-definition maps is no longer one-way information transmission, and the identities of the cartographers and the map users are no longer clearly divided. Some map users will also participate in mapping in the form of popular crowdsourcing to ensure the dynamic nature of map information. The map information is mutually transmitted between the map users and professional cartographers, and the cognitions of both sides are integrated under the traction of user demands, making the interaction feedback between the two more connected, ensuring that the personalized needs of the map users can be understood by the cartographers. From this, it can be known that the high-definition map information transmission model mainly has the characteristics of crowdsourcing, personalization, and dynamization. The discussion of the high-definition map information transmission model helps to accurately grasp the logical hierarchy of the high-definition map information system (HDMIS) and then clarify the information interaction relationships and methods at different levels, which has important guiding significance for strengthening the application effect of high-definition maps in the autonomous driving scenario [11]. In this regard, an HDMISM will be proposed below on the basis of the above information transmission model, and its data logical structure and application in the autonomous driving scenario will be analyzed.

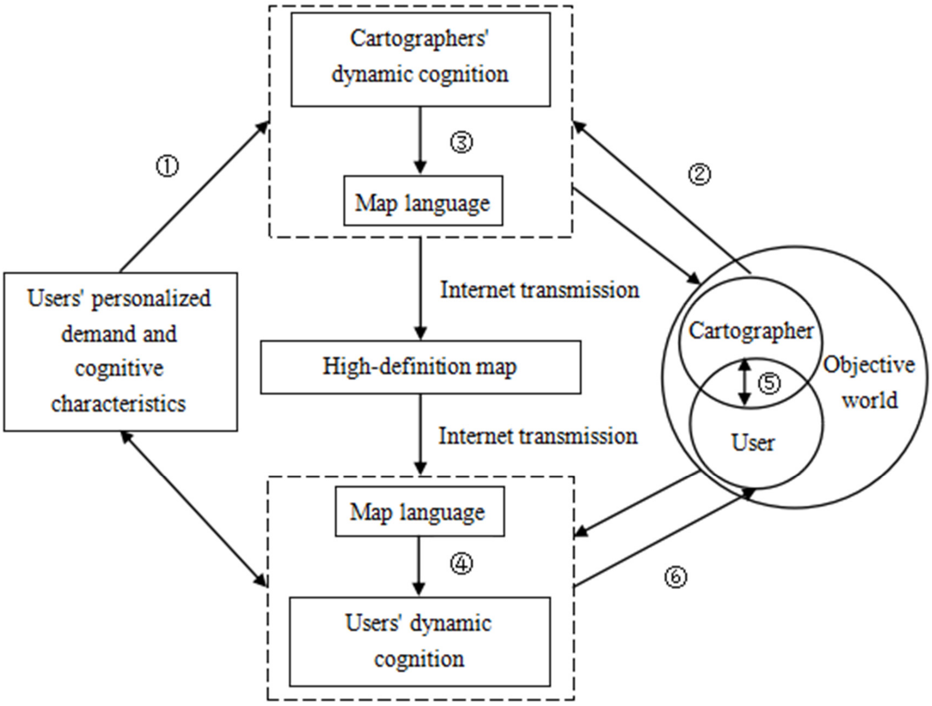

Figure 1. The information transmission model of high-definition map.

The academic community, map vendors, and auto companies have continuously increased their attention on the HDMIS but failed to unify their understanding of its data logical structure [12]. For example, in China, He Yong and others believed that the HDMIS can be divided into the traffic sign information layer, the lane line information layer, the lane network information layer, and the road network information layer [13]. The German Bosch Group (BOSCH) divided the HDMIS into the dynamic data layer, the semi-dynamic data layer, the semi-static data layer, and the static data layer [14]. The Li Keqiang team from Tsinghua University in China divided the HDMIS for autonomous driving into a total of seven layers: the road-level road network layer, the traffic information layer, the road-lane connection layer, the lane-level road network layer, the map feature information layer, the dynamic perception container layer, and the intelligent decision support layer [15]. HERE, a company under Nokia in Finland, based on cloud services, divided the HDMIS into the road model layer, the lane model layer, and the positioning model layer [16]. In China, E-Maptech Technology Co., Ltd., jointly joined hands with Tsinghua University in Beijing, Guoqi Intelligent Connected Automobile Research Institute Co., Ltd. (Beijing, China), Beijing NavInfo Technology Co., Ltd. (Beijing, China), Baidu Online Network Technology (Beijing) Co., Ltd. (Beijing, China), Amap Software Co., Ltd. (Beijing, China), and China Wuhan Zhonghaiting Data Technology Co., Ltd. (Wuhan, China) and more than 20 map vendors, auto manufacturers, and software and hardware vendors in the field of autonomous driving to be responsible for formulating the "Automatic Driving Map Collection Element Model and Exchange Format" standard. This standard divided high-definition maps into the collection scene basic information layer, the road traffic sign layer, the road traffic marking layer, other road safety facility layers, and the intelligent roadside equipment layer [17].

The division of the HDMISM mentioned above was mainly based on different perspectives, and the resulting division results were different and could not be unified. However, taken together, it can be found that high-definition maps mainly include three aspects: rich static road data information, dynamic driving environment information, and user-personalized demand information [18]. Static road data information mainly describes the static data of the road and the environment, and this type of data has a lower update frequency and longer timeliness; the dynamic driving environment information includes real-time road information and vehicle dynamic information, the real-time road information mainly refers to the road condition information at the macro level, and the vehicle dynamic information mainly refers to the instantaneous information of the local traffic scene centered on the vehicle, while the user-personalized demand information mainly refers to various types of demand information and characteristics of passengers, drivers, or map platform administrators. The existing research results have not focused on considering user demand information, and this paper believes that user-personalized demand information is also important information and an important driving force for the optimized development of high-definition maps and needs to be considered separately. In this regard, based on the division characteristics of people's HDMIS mentioned above, combined with standards such as the OpenDRIVE formulated by Germany, the "Navigation Data Standard" jointly developed by several multinational enterprises in Europe, the "Geographic Data Files" formulated by the European Standardization Committee, the "Road High-Definition Navigation Electronic Map Data Specification" formulated by China, and the "Intelligent Transportation System Intelligent Driving Electronic Map Data Model and Exchange Format" created in China [19], this paper believes that the HDMIS can be divided into a static map layer, real-time road data layer, vehicle dynamic data layer, and user model layer. The data of the four layers form the whole of the HDMIS, that is, the four-layer HDMISM. This information system covers traditional static map information (map), information considering the constant changes in the road (road), the instantaneous environment information around the vehicle (vehicle), and user demand information (person), taking "map, road, vehicle, person" as the main consideration elements, which clearly define the system thinking of "map-road-vehicle-person" and can more conveniently express the logical relationship of map data in the automatic driving scene. As shown in Figure 2, it is the approximate contents contained in the four levels. Later, the contents of different data levels will be expounded to provide references for research on high-definition map data association, the discussion of information interaction methods, etc., which has great significance for the development of high-definition maps.

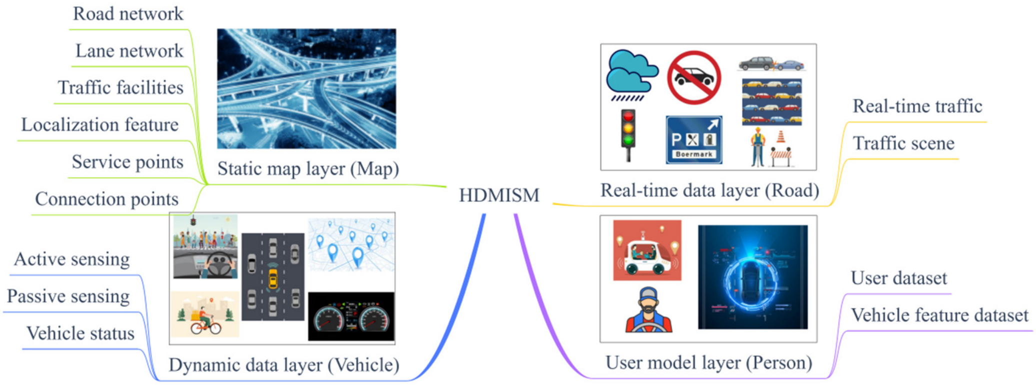

Figure 2. Information system model of high-definition map.

2.1. Static Map Layer

This layer of HDMIS is the basic data upgraded and optimized based on traditional navigation electronic maps, with roads as the main body, expressing more refined and richer traffic environment information, service point information, and information connecting with other transportation systems [20]. The static map layer contains various types of static data (Figure 3), which can accurately describe the static traffic environment and help autonomous vehicles understand the driving environment and control the vehicle's driving status.

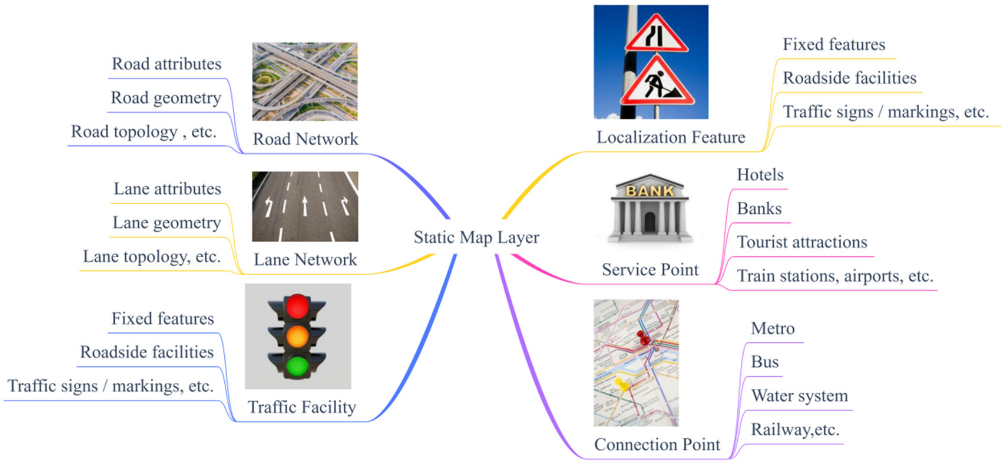

Figure 3. Static map layer of HDMIS.

Road network information mainly includes data such as road direction, road baseline, and road intersections, which can describe the relationship between road geometry and traffic facilities, providing global navigation information for autonomous vehicles and supporting road-level route planning. Lane network information is more detailed than road network information, mainly providing detailed information about lanes for autonomous vehicles, such as lane passage direction, curvature, slope, width, etc. [21]. It also has a more detailed description of lane baselines, lane markings, and lane baseline connection points, which can support lane-level path planning. Traffic facility information mainly describes point, linear, or area traffic facility information such as traffic lights, roadside telephone booths, guardrails, soundproof walls, traffic signs, toll stations, landmark buildings, etc. It is the long-term data of the HDMIS. Traffic facility information contains rich national geographic data, so the government is required to work together with the high-definition map management center and related enterprises to ensure the security of these basic data [22]. The positioning feature reference layer is derivative positioning service information, mainly released by different enterprises, which can complement basic geographic information data. Combined with the traffic facility information layer, it can provide positioning services for autonomous driving scenarios under no-signal or weak-signal conditions. With the gradual enrichment of people's needs, service point information in navigation electronic maps is also included in high-definition maps. Service point information includes service area entrances, hotels, rest areas, restaurants, train stations, ski cable car stations, banks, tourist attractions, toll stations, stadiums, airports, etc. Such service point information can not only meet the personalized needs of users but also serve as feature references to assist vehicle positioning [23]. Different passengers or drivers have different lengths of routes, and the transportation tools they need to take are also diversified. Incorporating the connection point information of other transportation systems such as subways, buses, waterways, and railways into high-definition maps could enable people to transfer conveniently.

Overall, in the autonomous driving scenario, the static map layer of the HDMIS can provide rich, detailed, comprehensive, and accurate road information and environmental information (such as road boundaries, lane boundaries, and lane centerlines covered by snow, water, or leaves) for autonomous driving vehicles, thereby guiding the vehicles to drive correctly and safely. The validity time of static map layer data is relatively long, the update frequency is relatively low, the cycle is relatively long, and the update cost is also relatively high, but the static map layer is the most important data layer of high-definition maps and lays an important data foundation for other data layers.

2.2. Real-Time Data Layer

This layer of HDMIS mainly focuses on the real-time traffic conditions of roads and lanes. This type of data has a higher update frequency and has an important impact on the real-time driving route of vehicles in autonomous driving scenarios. The real-time data layer has a large variety of information, which comes from vehicle sensors, meteorological bureaus, road management departments, traffic management departments, and road sensor networks but can be categorized into two types: real-time traffic information and traffic scene information (Figure 4).

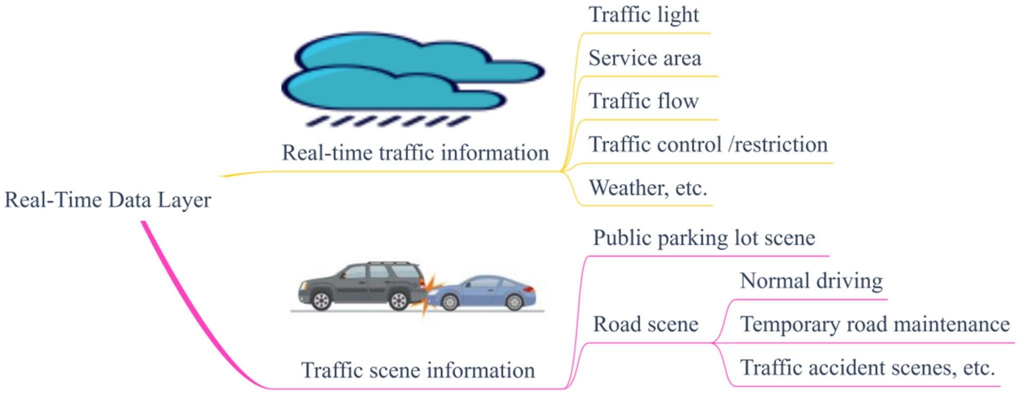

Figure 4. Real-time data layer of HDMIS.

Real-time traffic information can affect the vehicle driving route in autonomous driving scenarios [24], can support vehicles that access the HDMIS to change the driving route, and can help vehicles optimize navigation decisions. Traffic scene information is a supplement to real-time traffic information, which can provide relevant information about public parking lot scenes for autonomous driving vehicles, as well as provide relevant information about normal driving scenes, temporary road maintenance scenes, and traffic accident scenes, providing support for autonomous parking of autonomous driving vehicles and ensuring the optimization of vehicle navigation decisions.

To sum up, this layer can provide real-time traffic information for autonomous driving vehicles, avoiding delays in travel time due to congestion during driving and the occurrence of dangerous situations due to poor road conditions. The update frequency of the information of the real-time data layer is relatively high, which is between that of the static data layer and the dynamic data layer, and can provide important references for global route planning and optimization.

2.3. Dynamic Data Layer

The dynamic data layer mainly focuses on autonomous driving vehicles, paying attention to the driving behavior of vehicles and the change in the surrounding local scenes in the autonomous driving scenario. Vehicles obtain dynamic information through active and passive sensing methods and simultaneously perform instantaneous control of vehicles in combination with the instantaneous state information of the vehicle [25] (as shown in Figure 5).

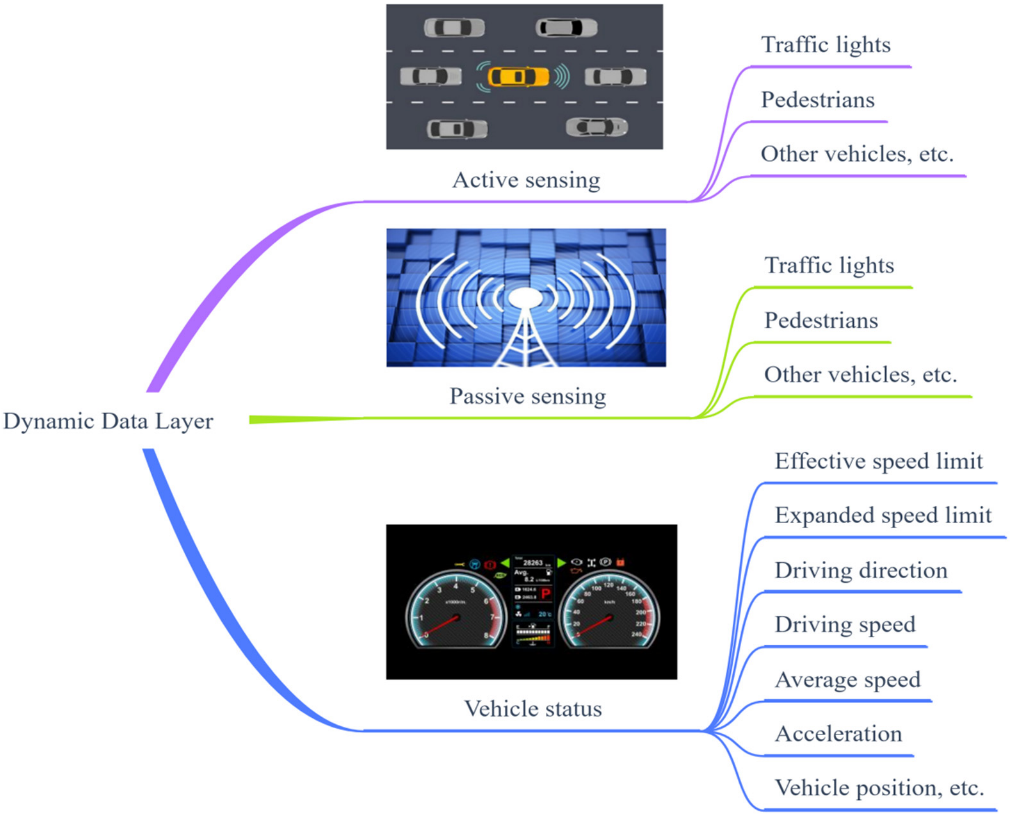

Figure 5. Dynamic data layer of HDMIS.

Active sensing dynamic information refers to the surrounding traffic signals, pedestrians, other vehicles, and other environmental information [26] that autonomous driving vehicles directly obtain through their own radar, cameras, and other sensors. The dynamic information of the local road scene provided by non-autonomous vehicle sensor systems such as roadside units (RSUs) is passive perceptual dynamic information. For example, the cloud distributes intersection information and traffic accident information to autonomous vehicles, helping them deal with blind spots when turning at intersections in advance, modify travel paths, and so on, thereby avoiding traffic accidents or becoming stuck near traffic accident scenes [27]. Passive sensing dynamic information makes up for the shortcomings of the incomplete active perception of autonomous vehicles and provides a guarantee for the safe operation of autonomous driving. In addition, the status information of autonomous vehicles, such as the vehicle's position, driving direction, current speed, and acceleration, also needs to be considered to ensure the safe driving of autonomous vehicles. In this way, autonomous vehicles can effectively predict special scenes, such as reverse driving, overtaking, abnormal vehicle temporary parking, and running red lights, and then take timely countermeasures and reasonably control the vehicle to avoid collisions.

The information of the dynamic data layer has a very high update frequency. Information acquisition is mainly carried out by vehicle-mounted sensors, and by cooperating with the information of the static map layer and the real-time data layer, it can ensure the efficient and safe driving of autonomous vehicles and then meet the user needs from the user model layer.

2.4. User Model Layer

The user model layer of the HDMIS mainly focuses on data sharing based on user (passengers and drivers at L2/L3 levels) requirements, providing services for them. The main data types include user data sets and vehicle characteristic data sets (Figure 6) [28].

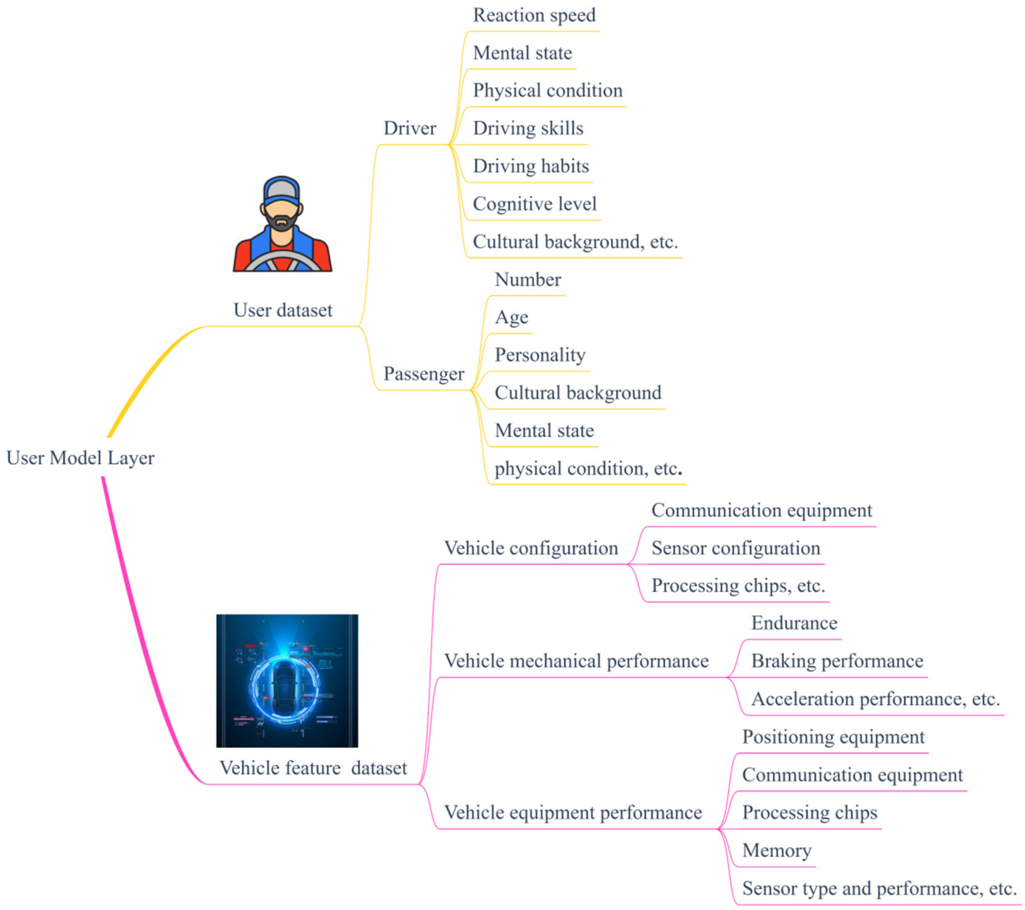

Figure 6. User model layer of HDMIS.

Drivers are involved in the driving of low-level autonomous vehicles, and the characteristic information such as their reaction speed, mental state, physical condition, driving skills, driving habits, cognitive level, cultural background, and driving experience all affect the vehicle operation. Therefore, the characteristic information of the driver needs to be included in the user model layer. In addition, the characteristic information of the passengers of autonomous vehicles, such as the number, age, personality, cultural background, mental state, and physical condition, also affects the driving of autonomous vehicles [29]. In order to better meet the needs of users, it is necessary to include the relevant characteristic information of users in the user model layer of the high-definition map. In addition, the characteristic data of the vehicle's configuration, mechanical performance, and equipment performance determine the operation control of the autonomous vehicle. This is a clear difference from the vehicle status information in the aforementioned dynamic data layer, but the user layer needs to cooperate with the vehicle status information in the dynamic data layer to optimize vehicle control.

The above four data layers cooperate with each other to provide perception, positioning, decision-making, and control services for autonomous vehicles. However, the mutual cooperation of the data at these levels requires the support of some key technologies. The following will present two relatively key technologies to provide support for the update of high-definition maps, the formation of local maps, and so on.

3. Key Technologies of High-Definition Map Information System

The complex traffic environment has an important influence on the operation control and driving route planning of autonomous vehicles. Timely updates of map information can enhance the predictive ability of autonomous driving for complex traffic environments and avoid the negative effects brought about by complex traffic environments [30]. Thus, updating the HDMIS and the information distribution technology has become key. In the intersection scenario, due to the characteristics of diversity and complexity of the intersection, the driving safety of autonomous vehicles at the intersection is greatly reduced, and it is necessary to construct a local information security framework for the intersection to provide a guarantee for the safe driving of autonomous vehicles. The following will propose effective key technologies for information updates and a safety information framework for intersections for the four-layer integrated high-definition map to support the safe driving and efficient passage of autonomous vehicles.

3.1. Cloud–Edge–Vehicle Collaborative Update Mechanism

The safe driving of autonomous vehicles requires the support of accurate information on high-definition maps, and the accuracy, timeliness, and richness of high-definition map information need to be maintained through timely updates. A reasonable and effective update mechanism can ensure the timely and efficient update of high-definition maps and provide assistance for autonomous driving. This paper believes that the update of high-definition map information can be divided into long-term updates and dynamic updates, among which long-term updates are updates of static data such as roadside facilities, lane networks, and road networks. The data for this type of update mainly come from professional collection vehicles and crowd-hired vehicles [31]. The cycle of long-term updates is longer and the frequency is lower, but the valid time of the data is relatively long. Dynamic updates mainly take autonomous driving vehicles as the focus, preliminarily processing and updating related information through roadside facilities, crowd-hired vehicles, and autonomous driving vehicles [32], such as the dynamic environment information around the vehicles, temporary obstacle information, traffic congestion information, temporary road construction information, road marking information, etc. Then, the updated information is uploaded to the central cloud, and the cloud distributes local dynamic information such as temporary signs, traffic flow, and traffic accidents to different vehicles to help different autonomous driving vehicles better optimize route planning and vehicle control. When distributing local dynamic information, the cloud will consider the characteristic situation of the autonomous driving vehicles, including vehicle attribute characteristics, such as vehicle type and configuration, vehicle operating direction, and vehicle speed, and territorial characteristics, such as the current location of the vehicle, destination, and passing areas. The cloud, edge, and vehicle ends cooperate with each other to ensure the timely update and distribution of high-definition map information, forming a cloud–edge–vehicle collaborative update mechanism (Figure 7), which ensures the self-adjustment, organization, and update of high-definition maps and provides services for the safe driving of autonomous driving vehicles.

It should be noted that in the cloud–edge–vehicle collaborative update mechanism, the edge can perform a small amount of computing tasks, which greatly reduces the computing burden of the central cloud so that the central cloud does not have difficulty processing data in a timely manner due to the excessive amount of data and can then process more data efficiently. This is significantly different from the traditional central cloud computing method, which transmits all data to the cloud computing model for centralized processing. However, as the amount of data continues to increase, this processing method has too much computing burden, and then it is unable to complete data processing in a timely manner, which is not conducive to the timely acquisition of traffic information by autonomous driving vehicles. In the cloud–edge–vehicle collaborative update mechanism, after the edge and vehicle end update the local information, it is uploaded to the central cloud, which can greatly reduce the computing amount of the central cloud and improve the data processing speed and quality.

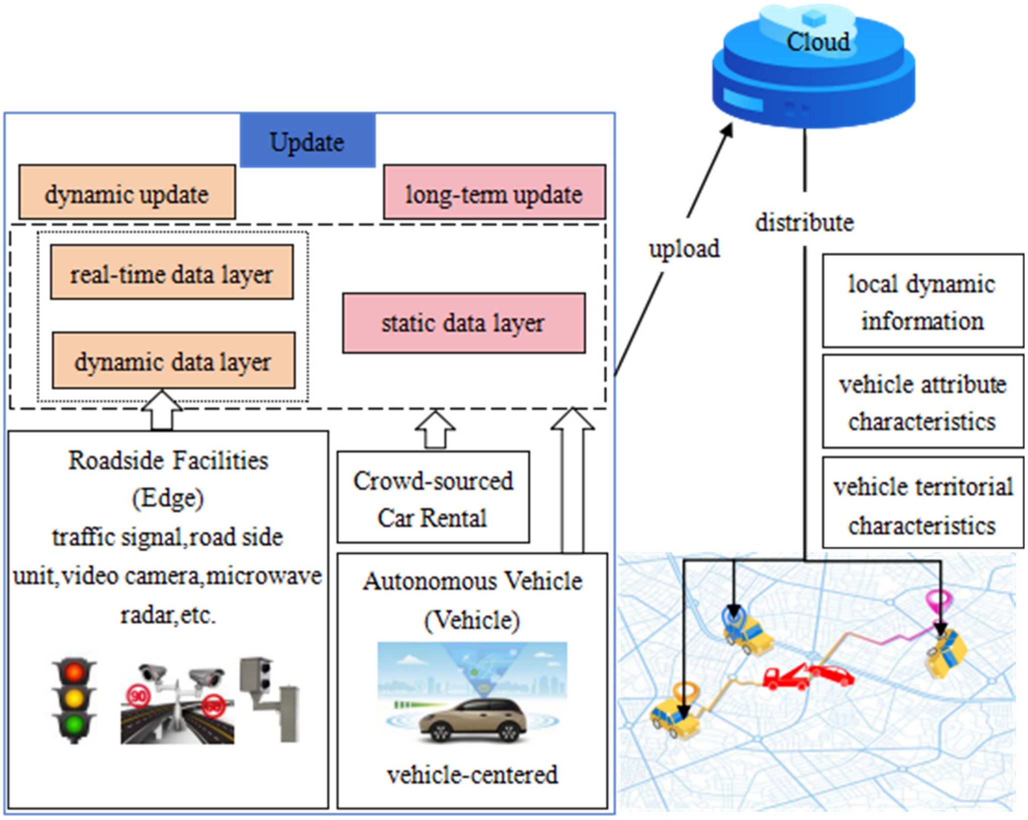

Figure 7. Cloud–edge–vehicle collaborative update mechanism.

3.2. Intersection Safety Information Framework

Intersections have the characteristics of diversity, complexity, real-time nature, and precise driving position constraints [33]. Different traffic participants have obvious differences in types, passage methods, and passage decision-making capabilities, which makes the traffic environment at the intersection change rapidly, thereby resulting in more difficult driving planning decisions and controls of autonomous driving vehicles at the intersection. It is necessary to consider safety for the intersection, such as constructing an intersection safety information framework of “road network—lane network—intersection signs—scene mode” (Figure 8), which can better assist autonomous driving vehicles to safely pass through intersections with complex traffic environments. The intersection safety information framework can better predict the conflict zone for autonomous driving vehicles, visually express the intersection situation, and also divide the priority of the right of way according to traffic rule constraints to provide guarantees for local path planning and vehicle control of autonomous driving. In the intersection safety information framework, rich and detailed information such as roads, lanes, and marking lines are provided by the road network, lane network, and intersection signs. The scene mode includes information such as roundabout information, isolation belt information, guide flow line information, intersection space obstacle information, and lane change rules, which can provide scene mode references for the correct driving of autonomous driving vehicles.

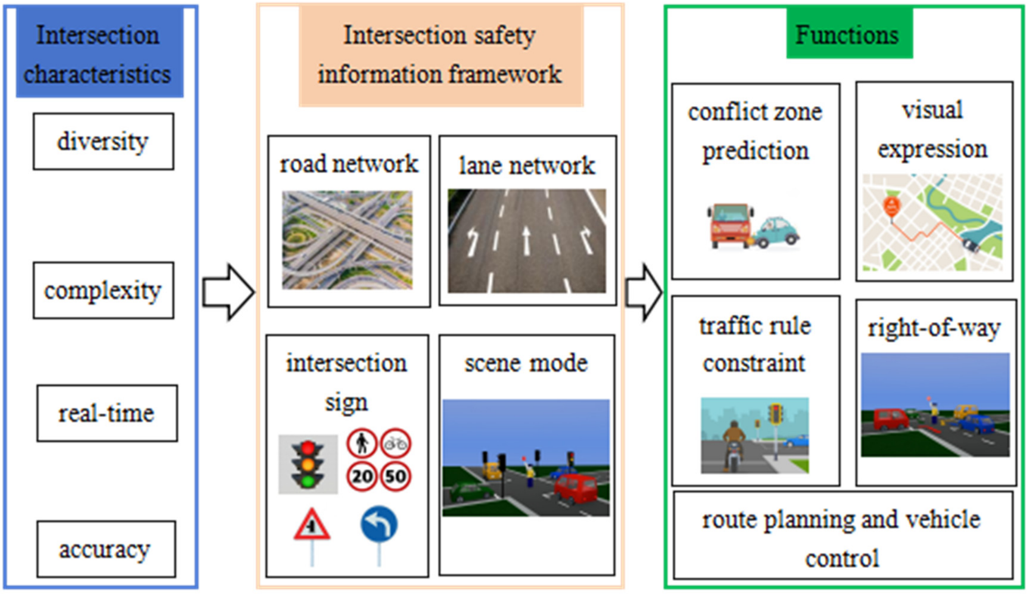

Figure 8. Intersection safety information framework.

Two key technologies can provide important support for the update and application of high-definition maps. Regarding the application of the high-definition map information system model in the autonomous driving scenario, logical analysis and application case analysis will be carried out in the next section.

4. The Application of the HDMISM in the Autonomous Driving Scenario

4.1. Analysis of the Application Logic of the Four-Layer Integrated HDMISM

The HDMIS plays a multifaceted role in the autonomous driving scenario, such as being able to provide four aspects of support for autonomous driving vehicles, namely, scene perception, map matching and positioning, driving decision making, and vehicle control, and providing guidance for the safe and efficient driving of autonomous driving vehicles. In the autonomous driving scenario, the scene perception support provided by the HDMIS mainly provides information beyond the active perception for autonomous driving vehicles. The complex traffic environment makes the sensing devices equipped on autonomous driving vehicles limited and unable to clearly perceive the boundaries of roads, lanes, etc. At this time, the HDMIS can provide sensing services for autonomous driving vehicles to ensure that they can drive safely [34]. The map matching and positioning support provided by the HDMIS are mainly to provide precise positioning services for autonomous driving vehicles, especially when laser radars, global navigation satellite system/inertial measurement unit, etc., are damaged or the signal is missing, the HDMIS can provide reliable and precise positioning services [35]. In terms of driving decision making, the complex traffic environment makes it difficult for autonomous driving vehicles to merely rely on their own sensing and recognition systems to capture relevant information, such as local path driving rules, dynamically changing local traffic scenarios, etc. The HDMIS acquires the latest and rich dynamic and static traffic information through roadside facilities, crowdsourced vehicles, autonomous driving vehicles, and professional collection vehicles and can provide key information for autonomous driving vehicles and provide support for them to make scientific driving decisions. In terms of vehicle control, the HDMIS can control the driving behavior of autonomous driving vehicles through control algorithms based on information such as the real-time traffic environment, driving regulations, and lane curvature, including acceleration and deceleration, lane changing, steering, etc. Outlining how the four-layer integrated data logic proposed in this paper can play the above roles in an actual autonomous driving scenario is the goal of this study. According to the wheeled robot control process [36], in the autonomous driving scenario, the application logic of the HDMISM should be "perceive the environment—match and position—plan and decide—control the vehicle" (Figure 9).

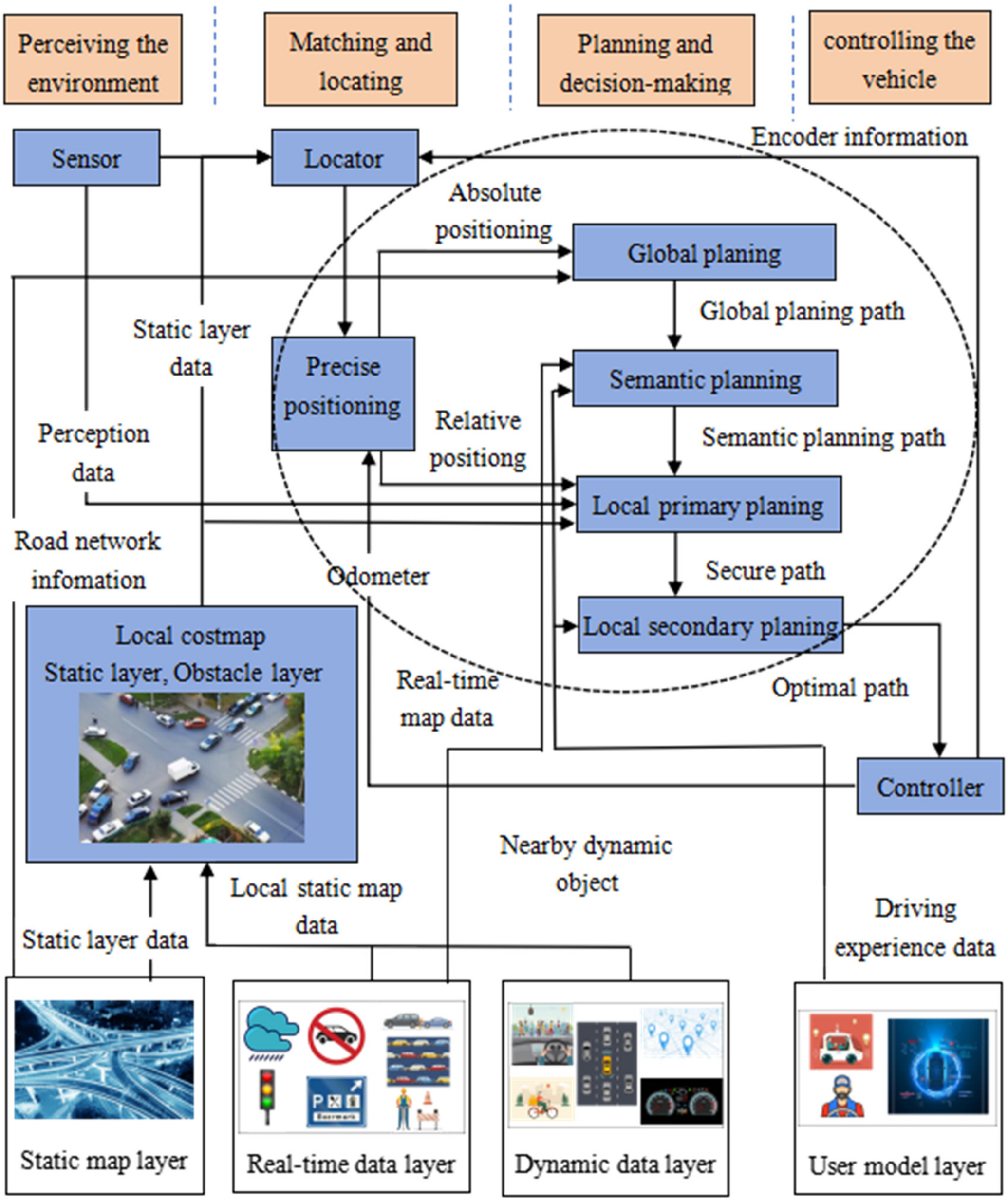

Figure 9. The application logic of the four-layer integrated HDMISM.

Perceive the environment: In the actual application process, autonomous driving vehicles first perceive the surrounding environmental information through the mounted sensors to roughly determine the approximate location where the vehicles are. Then, with the help of the locator to receive the perceived data, combined with the data of the static map layer, high-quality data results can be generated, and then accurate perception results of the surrounding environment can be obtained.

Match and locate: By using the detected data (with semantic meaning) to match the static map layer data, the purpose of relative positioning can be achieved. After converting the coordinates, absolute positioning can be realized, providing a basis for route planning and decision making.

Planning and decision making: In the actual application scenario of autonomous driving, high-definition maps need to use data from different levels in the information systems to achieve hierarchical planning of the path and then guide and constrain the driving of autonomous driving vehicles. Usually, hierarchical planning can be divided into global planning, semantic planning, local primary planning, and local secondary planning. Different levels of planning refer to different map data [37]. In global planning, it is necessary to determine the global route between the starting point and the end point based on the absolute positioning result in matching and positioning, combined with the road network data in the static map layer, to obtain the global planning path. In semantic planning, it is necessary to introduce the driving experience data in the user model layer and the map data in the road real-time data layer on the basis of the global planning path and then form the semantic planning path. In local primary planning, it is necessary to form a new safe driving path based on the semantic planning path, local cost map (a map formed by combining the local range data of the dynamic data layer, real-time data layer, and static map layer, including the static layer and obstacle layer), and relative positioning data. In local secondary planning, the main purpose is to optimize the local primary planning path (optimize the path), considering the comfort and safety of autonomous driving, in order to meet the customers' demand for comfort and safety. This mainly introduces the driving experience data in the static map layer and completes secondary planning based on the local primary planning path.

Control the vehicle: After the local secondary planning path is generated, it is converted by the controller into control instructions that can be recognized and executed by the robot in order to further control the driving of the vehicle, the control information is fed back to the locator in order to refresh the position information, and then this process is looped.

The application logic of the HDMIS elaborated in Figure 9 is applicable to all scenarios of autonomous driving. In the autonomous driving scenario, the application of high-definition maps follows the process of "perceiving the environment—matching and locating—planning and decision-making—controlling the vehicle". The following will analyze the supporting role played by the above application logic through specific application scenario cases.

4.2. Application Case Analysis of HDMIS

The impact of traffic events is the most complex, and it presents the highest challenge to autonomous driving decision making. Under the influence of traffic events, the supporting role of the HDMIS is very important [38]. Taking traffic accidents as an example, according to the application logic of the four-layer integrated information system model, the supporting flow chart as shown in Figure 10 can be obtained. After the user defines the starting point and end point of the journey, the HDMIS plans the route for the entire journey based on the information in the static data layer (road network information, service point information, positioning information, etc.) and the information in the user model layer (driving experience information, etc.). During the driving process, when encountering special traffic events that pose a threat to the travel efficiency and travel safety of passengers, the HDMIS will obtain the latest accessible road information and avoid the scene of the traffic event [39]. Then, through the knowledge graph of the HDMIS, it re-plans the local driving path for autonomous driving vehicles and formulates a driving strategy according to the dynamic traffic environment information around the vehicles, driving speed, driving acceleration, and driving direction, including steering, changing lanes, etc.

As shown in Figure 10 above, in the autonomous driving scenario, the data of the four levels of high-definition maps cooperate with each other so that high-definition maps can better plan various levels of paths and optimize the paths according to user requirements. When encountering traffic accidents, it can promptly propose new paths and control the vehicle to avoid the accident site. Overall, in various autonomous driving scenarios, the HDMIS plays an important supporting role. In the future development of the autonomous driving industry, high-definition maps still have a non-negligible position. For this reason, high-definition maps will still be a valued research object in the future, and its information system model will become more and more perfect and standardized.

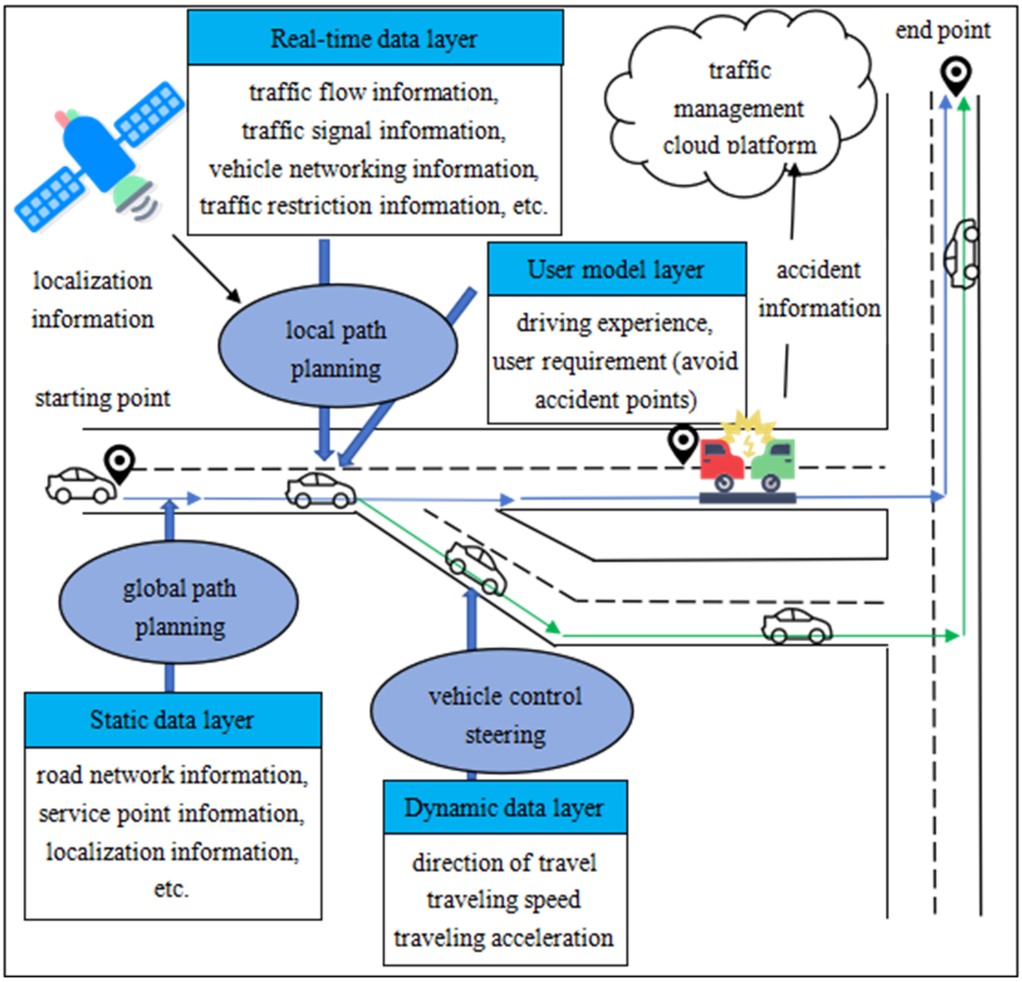

Figure 10. The supporting role of HDMIS.

5. Discussion

The HDMISM is a comprehensive concept, and its data logical structure is different, resulting in differences in data association methods. Unifying the data logical structure of the HDMISM is of great significance for formulating high-definition map production standards, unifying information interaction relationships, and standardizing map data association, etc.

The four-layer integrated HDMISM proposed in this paper forms a simple model structure with the four core elements of "map, road, vehicle, and person" as key nodes, making the data logical structure of the system model clearer. In the autonomous driving scenario, the "map" is the most basic tool, and no matter what the data logical structure of the high-definition map is, it cannot be separated from the static map data information. The "road" is a process that the autonomous vehicle must go through, and in this process, what dynamic influencing factors will be faced is what the autonomous vehicle needs to consider and understand. The "vehicle" is the carrier of autonomous driving, which is indispensable in the autonomous driving scenario, but the environment around the vehicle changes all of the time, and relevant information needs to be obtained in time to properly control the vehicle's travel. "Person" is the cause of vehicle travel in the autonomous driving scenario, and even for an autonomous vehicle without passengers, its travel purpose must also originate from the "person". In this regard, this paper believes that "map, road, vehicle, person" are the core elements of the high-definition map in the autonomous driving scenario, and it is feasible to divide the data logically with them as key nodes. The proposed map information system model has an important reference value for unifying the data logical structure of the high-definition map information system model.

L5-level autonomous driving is the pursuit goal in the future field of autonomous driving. At that time, autonomous vehicles will be able to drive highly autonomously but still need the support of the four core elements of "map, road, vehicle, person". Although some scholars believe that "sensors + AI" can replace the human senses and brain to complete vehicle driving without the need for maps, this may be limited to local autonomous driving. In long-distance autonomous driving, rich data support from high-definition maps is still required, especially real-time road information (such as road sections with floods or landslides) that traditional maps do not have. Therefore, in the future production of high-definition maps, "map, road, vehicle, person" can be key factors to consider, unifying the production standards of high-precision maps and ensuring that high-definition maps can achieve functions such as self-learning, self-adaptation, and self-evaluation.

6. Conclusions

The continuous standardization and improvement of the HDMIS can promote the development of the autonomous driving industry because high-definition maps provide important support for autonomous driving vehicles at four levels: perception, positioning, decision making, and control. This article proposed a four-layer architecture HDMISM and elaborated on the contents of each level in the model and the role played in the autonomous driving scenario. This article also discussed two key technologies, the map update mechanism combining cloud–edge–vehicle and the composition of safety information in the intersection scenario, and explored the support provided by the HDMIS to the perception, positioning, decision making, and control of autonomous driving vehicles combined with these technologies. The improvement of the HDMISM not only promotes the development of the autonomous driving industry but also promotes the digitalization of transportation infrastructure and has a non-negligible driving effect on the realization of smart transportation. However, at present, the data logical structure of the high-definition map information system model has not been unified yet, and relevant research results are still relatively few. In this regard, it needs to be strengthened in future research. In future research, validity verification will be carried out for the model structure proposed in this article so as to promote the application of this research result in the field of high-definition maps.

Author Contributions: Conceptualization, X.S.; Methodology, Z.Q.; Validation, Z.Y.; Writing—original draft, Z.Q.; Writing—review & editing, X.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are grateful to the School of Transportation, Southeast University, China, for providing the research platform and grateful for the valuable suggestions from the relevant teachers at the university.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Siejek, M.; Kasza, D.; Wajs, J. Methodology of Spatial Data Acquisition and Development of High-Definition Map for Autonomous Vehicles—Case Study from Wrocław, Poland. *Civ. Environ. Eng. Rep.* **2024**, *34*, 87–103. [CrossRef]
2. Jain, S.; Ahuja, N.J.; Srikanth, P.; Bhadane, K.V.; Nagaiah, B.; Kumar, A.; Konstantinou, C. Blockchain and Autonomous Vehicles: Recent Advances and Future Directions. *IEEE Access* **2021**, *9*, 130264–130328. [CrossRef]
3. Young, T.L.; Hun, M.J.; Almirah, P. Object Detection of Road Facilities Using YOLOv3 for High-definition Map Updates. *Sens. Mater.* **2022**, *34*, 251–260. [CrossRef]
4. Hui, N.; Jiang, Z.J.; Cai, Z.L.; Ying, S. Vision-HD: Road change detection and registration using images and high-definition maps. *Int. J. Geogr. Inf. Sci.* **2024**, *38*, 454–477. [CrossRef]

5. Ma, B.; Liu, Y.; Na, X.; Liu, Y.; Yang, Y. A shared steering controller design based on steer-by-wire system considering human-machine goal consistency. *J. Frankl. Inst.* **2019**, *356*, 4397–4419. [CrossRef]
6. Sun, H.T.; Zhang, P.F.; Peng, C.; Ding, F. State-aware UGV H_∞ event-triggered path tracking control. *J. Hunan Univ. (Nat. Sci. Ed.)* **2022**, *49*, 34–42. [CrossRef]
7. Ding, F.; Li, Q.L.; Lei, F.; Liu, J. Research on human-machine collaborative steering predictive control strategy of torque correlation driven assistance under dynamic trajectory tracking*. *J. Mech. Eng.* **2022**, *58*, 143–152. [CrossRef]
8. Ding, F.; Shan, H.Y.; Han, X.; Jiang, C.; Peng, C.; Liu, J. Security-Based Resilient Triggered Output Feedback Lane Keeping Control for Human–Machine Cooperative Steering Intelligent Heavy Truck Under Denial-of-Service Attacks. *IEEE Trans. Fuzzy Syst.* **2023**, *31*, 2264–2276. [CrossRef]
9. Zhang, F.Y.; Shi, W.Z.; Chen, M.; Huang, W.; Liu, X. Open HD map service model: An interoperable high-Definition map data model for autonomous driving. *Int. J. Digit. Earth* **2023**, *16*, 2089–2110. [CrossRef]
10. Yin, Z.C.; Qi, R.Y.; Ying, S. The information transmission model of high-definition map for autonomous driving. *J. Wuhan Univ. (Inf. Sci. Ed.)* **2024**, *49*, 527–536. [CrossRef]
11. Choi, I.H.; Kim, E.M. Automatic Construction of Road Lane Markings Using Mobile Mapping System Data. *Sens. Mater.* **2022**, *34*, 2625–2635. [CrossRef]
12. Cudrano, P.; Gallazzi, B.; Frosi, M.; Mentasti, S.; Matteucci, M. Clothoid-Based Lane-Level High-Definition Maps: Unifying Sensing and Control Models. *IEEE Veh. Technol. Mag.* **2022**, *17*, 47–56. [CrossRef]
13. He, Y.; Lu, H.; Wang, C.X.; Yang, M.; Wu, T. Investigation on the production method of lane-level high-accuracy map. *J. Chang. Univ. (Nat. Sci. Ed.)* **2015**, *35*, 274–278. [CrossRef]
14. Shim, I.; Choi, J.; Shin, S.; Oh, T.-H.; Lee, U.; Ahn, B.; Choi, D.-G.; Shim, D.-H.; Kweon, I.-S. Research on autonomous driving system based on complex traffic environment. *Ieee Trans. Intell. Transp. Syst.* **2015**, *16*, 1999–2013. [CrossRef]
15. Li, K.Q.; Dai, Y.F.; Li, J.W. Development Trends and Proposals of Intelligent connected Vehicles. *Intell. Connect. Veh.* **2018**, *1*, 12–19.
16. Yi, J. HERE Launches a Global LiDAR Database for 3D Modeling. *China Surv. Mapp.* **2022**, *3*, 80. [CrossRef]
17. Huang, C.; Yin, T.; Wang, J.M. Discussion on the Standardization Construction of High-Precision Maps. *China Stand.* **2021**, *21*, 89–93.
18. Zhan, J.; Guo, C.; Lei, T.T.; Qu, Y.Q.; Wu, H.B.; Liu, J.N. Investigation of high-definition map data format. *J. Image Graph.* **2021**, *26*, 36–48.
19. Cai, Z.L.; Wang, M.Q.; Li, B.Z.; Kang, M.J. Study on high-accuracy map data model and format standards. *J. Geomat.* **2023**, *48*, 30–34. [CrossRef]
20. Liu, R.; Wang, J.L.; Zhang, B.Q. High-Definition Map for Automated Driving: Overview and Analysis. *J. Navig.* **2020**, *73*, 324–341. [CrossRef]
21. Xu, X.Z.; Gao, S.A.; Tao, M.X. Investigation on the caching mode of high-definition map data. *IEEE Wirel. Commun. Lett.* **2021**, *10*, 1390–1394. [CrossRef]
22. Fei, W.K. A Dynamic Generation Method of Local Relative Position for High-Definition Maps and Its Applications. *Bull. Surv. Mapp.* **2023**, *6*, 1–5. [CrossRef]
23. Jiang, H.W.; Zhang, Y.J.; Li, L.M.; Yang, Y. Research on the Data Storage and Exchange Model of Basic Geographical Entity. *Bull. Surv. Mapp.* **2024**, *S1*, 120–125. [CrossRef]
24. Wang, L.Y.; Zhou, X.; Hu, W.; Liu, L.X.; Li, F.X. A High-Definition Map Data Engine Model for Autonomous Driving. *Surv. Mapp. Bull.* **2023**, *6*, 11–14. [CrossRef]
25. Zhou, J.; Guo, Y.; Bian, Y.A.; Huang, Y.; Li, B. Lane Information Extraction for High Definition Maps Using Crowdsourced Data. *IEEE Trans. Intell. Transp. Syst.* **2023**, *24*, 7780–7790. [CrossRef]
26. Endo, Y.; Javanmardi, E.; Gu, Y.L.; Kamijo, S. High Definition Map Aided Object Detection for Autonomous Driving in Urban Areas. *Int. J. Automot. Technol.* **2023**, *24*, 469–481. [CrossRef]
27. Gong, S.Y.; Zhao, L.; Wu, Y.L.; Sun, K.; Zhao, X.M.; Xu, Z.G. An Optimization Method for Roadside Unit Deployment Considering the Coexistence of Vehicle-to-Vehicle and Vehicle-to-Road Communications. *China J. Highw. Transp.* **2022**, *35*, 226–243. [CrossRef]
28. Zhao, Z.G.; Li, Y.; Hu, H.R.; Wang, P.; Chen, X.R. Detection of Driver′s Abnormal Behavior Under Emergent Collision Avoidance Conditions. *Automot. Eng.* **2022**, *44*, 412–425. [CrossRef]
29. Xu, L.; Lu, Y.; Sun, Z.Y.; Li, H.D. Personalized User Research Based on the Acceptance of Autonomous Vehicles. *Packag. Eng.* **2023**, *44*, 42–58. [CrossRef]
30. Krehlík, S.; Vanzura, M.; Skokan, A. Minimum required accuracy for HD maps. *J. Navig.* **2023**, *76*, 238–254. [CrossRef]
31. Feng, C.; Du, Q.Y.; Fan, X.Y.; Ren, F.; Xiong, L.Y.; Tian, Y.; Liu, W.H.; Wang, T.; Wang, Y.Z.; Zhng, B.C. Research on Crowdsourced Update of High-Definition Map Infrastructure Platform. *J. Geomat.* **2023**, *48*, 10–15. [CrossRef]
32. Zhao, M.S. Review of the Development of On-board Navigation to Autonomous Driving Electronic Maps. *Bull. Surv. Mapp.* **2023**, *6*, 6–10. [CrossRef]
33. Wu, B.; Zhu, X.C.; Liao, M.Z.; Liu, R. Safety Boundary Condition Model of Vehicle Conflict and Collision at Intersection. *J. Tianjin Norm. Univ. (Nat. Sci. Ed.)* **2019**, *39*, 62–66. [CrossRef]
34. Meng, L.Q. Research on the development trend of autonomous driving maps. *Acta Geod. Et Cartogr. Sin.* **2022**, *51*, 1029–1039.
35. Wang, J.W.; Sun Ch, C.; Zhao, J.; Hang, J.Y. Multi-layer Fuzzy Estimation Method of Road Section Capacity Under Traffic Events. *J. Transp. Syst. Eng. Inf. Technol.* **2023**, *23*, 100–110. [CrossRef]

36. Chen, D.W.; Zhu, Y.F.; Wang, D.; Wang, H.; Xie, X.; Zhang, X.P.; Han, Z. Love of Variety Based Latency Analysis for High Definition Map Updating: Age of Information and Distributional Robust Perspectives. *IEEE Trans. Intell. Veh.* **2023**, *8*, 1751–1764. [CrossRef]
37. Chiang, K.W.; Srinara, S.; Tsai, S.Y. High-Definition-Map-Based LiDAR Localization Through Dynamic Time-Synchronized Normal Distribution Transform Scan Matching. *IEEE Trans. Veh. Technol.* **2023**, *72*, 7011–7023. [CrossRef]
38. Li, B.; Guo, Y.; Zhou, J.; Tang, Y.; Dong, Q.; Li, Z. Development and Prospects of High Definition Map for Intelligent Vehicle. *Geomat. Inf. Sci. Wuhan Univ.* **2024**, *49*, 491–505. [CrossRef]
39. Zhang, Y.J.; Huang, W.; Liu, X.T.; Zhang, F.Y.; Wu, H.L.; Ying, S.; Liu, C. Investigation on the method of high-definition map data transmission. *Geomat. Inf. Sci. Wuhan Univ.* **2024**, *49*, 166. [CrossRef]