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Key Technologies and Prospect of Vehicle Infrastructure Cooperated Autonomous Driving (VICAD) 2.0

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Preface

Autonomous driving (AD) is one of the most complex tasks in the next five years in the field of artificial intelligence. The application of autonomous driving technology in the industry is essentially crossing the "Darwinian sea," full of challenges, uncertainties and opportunities.

While I have full confidence that AD will arrive, the path and timing are nothing but certain. Different technological paths lead to different commercial critical points. More importantly, the application of AD technology has an uncompromising principle of "safety," which requires full consideration of various factors such as current laws, regulations, policies, ethics, etc.

There are challenges between technological innovation and industrial application, which requires the true partnership among academia, cross-industry and policy makers. This is the reason why the Institute for AI Industry Research Institute (AIR), Tsinghua University and Baidu jointly initiated the "Apollo AIR" Program in 2021, to explore the road side intelligence to compliment vehicle AD. Our principle, methodology and preliminary results are released in this white paper titled "Key Technologies and Developing Prospect of Vehicle Infrastructure Cooperated Autonomous Driving (VICAD)" (referred to as "AIR Series White Paper").

With the strong support of the development and application of technologies such as C-V2X, edge computing, and cloud computing, the vehicle-infrastructure cooperated technology can effectively resolve the safety-related long tail faced by single-vehicle intelligence, while taking into account the operational design domain and economy. The vehicle-infrastructure cooperated autonomous driving (VICAD) introduces a more advanced set of higher-dimensional intelligent elements to intelligent vehicles. Data, computing power, and algorithms are not limited to single-vehicle intelligence, but evolving into cooperative intelligence, thus allowing the autonomous driving at different levels and intelligent connected vehicles to participate in the interaction of traffic information. With a high-dimensional perspective and real-time information transmission, the "senses" of intelligent vehicles will be further enhanced, to help make wiser judgments and decisions in complex traffic environments.

Vehicle-infrastructure cooperated technology is complementary to the single-vehicle intelligence, which is a high-level development pattern and an inevitable trend of autonomous driving. This is not only a technical approach, but also an industrial proposition. On the one hand, by developing the vehicle-infrastructure cooperated technology, autonomous driving becomes affordable and accessible to ordinary people, and the threshold for large-scale commercialization is greatly reduced. On the other hand, a cross-industry system project is established, accelerating the development of the automobile, communication, transportation, semiconductor and other industries. Detailed demonstration is completed in the "AIR White Paper 2.0" around these considerations. This white paper is not a conceptual paper, rather based on real industry needs and application scenarios and is intended to catalyze key changes.

In the Fall of 2022, I had a face-to-face exchange with colleagues from AIR of Tsinghua University and Baidu Apollo in Olympic Forest Park (Beijing). We discussed how artificial intelligence technology can be applied to traffic scenarios in the future and what is the future supported by the autonomous driving. At that time, the "AIR White Paper 2.0" was about to be published after nearly a year of intense discussion and work. The exploration of artificial intelligence, vehicle-infrastructure cooperated technology, and autonomous driving is a journey with endless innovation. The white paper will be also continuously updated with the iteration of artificial intelligence technology and the deepening of understanding of the industry.

I would like to thank all the colleagues who participated in the discussion, compilation and review, and sincerely hope that "Key Technologies and Developing Prospect of Vehicle Infrastructure Cooperated Autonomous Driving 2.0" becomes a new stimulus, to promote the technological advance and commercialization of vehicle-infrastructure cooperated autonomous driving.

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December 2022

Foreword

Autonomous driving technology is an important factor affecting the future development of the automobile industry. With the maturity of autonomous driving technology and the acceleration of commercialization, automobile is more than a driving tool, and its core value components shift from the drive system that reflects the power and operating system to the intelligent software system and the processing chip that embodies the level of autonomous driving, freeing the driver's hands, feet and eyes, fully constructing the entertainment, social, and consumption scenarios during travel, and stimulating the trillion-scale autonomous driving market.

When discussing autonomous driving, we typically refer to two terms: autonomous driving (AD)[1] and autonomous vehicles (AV). Additionally, we anticipate that vehicles will be capable of recognizing traffic signs, understanding traffic lights, identifying objects on the road, and executing real-time route planning, decision-making, and control – in other words, driving like a human. As the industry develops autonomous driving, there are two paths: progressive and leapfrogging. Original equipment manufacturers (OEMs) typically adopt the progressive path, loading low-level driving assistant systems, achieving mass production and commercialization, iterating algorithms through data, and ultimately achieving fully unmanned driving. In contrast, internet and startup companies often choose the leapfrogging path, utilizing multi-sensor fusion methods (such as cameras and LiDARs) to strive for the immediate maturity and large-scale commercialization of high-level autonomous driving technology, specifically L4 and above.

With the advancement of autonomous driving technology, the concept of Vehicle Infrastructure Cooperated Autonomous Driving (VICAD) has emerged [2], paving the way for a new era of development in the field [3]. VICAD builds on the foundation of autonomous driving (AD) and leverages the capabilities of road systems, cloud networks, and vehicle-to-vehicle coordination, as well as vehicle-to-road, vehicle-to-cloud, and vehicle-to-driver interactions. The ultimate goal is achieving fully autonomous driving.

Countries worldwide have recognized the significance of VICAD-related technologies, and substantial efforts have been invested in research and industrial applications. The United States initiated the Vehicle-Infrastructure Integration (VII) research program in 2004 and issued several programmatic documents, such as the Automated Vehicles Comprehensive Plan [4], and ITS Strategic Plan [5]. They led a series of research and verification demonstration projects, including IntelliDrive, Connected Vehicle Pilot, and CARMA. In Europe, several top-level design planning initiatives, such as the Connected Automated Driving Roadmap [6], Cooperative Intelligent Transport Systems and Services [7], and Cooperative, Connected, and Automated Mobility (CCAM)[8], have been launched based on ITS-G5 and 4G/5G

1. The United States defines the single-vehicle intelligent autonomous driving as the autonomous driving, and ERTRAC defines it as the automated driving.
2. CARMA (USA) proposed cooperative driving automation (CDA), and ERTRAC (Europe) proposed the concept of connected automated driving (CAD). With reference to foreign conditions and the current state of technological development in China, in this white paper, the vehicle-infrastructure cooperation is defined as vehicle infrastructure cooperated autonomous driving (VICAD).
3. For a detailed discussion on the technical route of autonomous driving, see Key Technologies and Developing Prospect of Vehicle Infrastructure Cooperated Autonomous Driving (2021).
4. https://www.transportation.gov/av/avcp
5. https://www.its.dot.gov/
6. Connected Automated Driving Roadmap[R]. The European Road Transport Research Advisory Council (ERTRAC)
7. https://www.car-2-car.org/about-c-its/
8. https://www.ccam.eu/

communication technologies. These initiatives have led to numerous research testing and deployment projects, such as eSafety, CVIS, Drive C2X, CAR2CAR, and C-ROADS, among others. Japan, as early as 2006, initiated the "Smartway Plan" as a next-generation transport infrastructure project. By integrating various functions of ITS, Japan established a nationwide vehicle integration platform providing services such as ETC, DSSS, and ASV for vehicles. In September 2017, Tokyo, Japan, issued the latest edition of the urban master planning, the Grand Design of Urban Construction - Tokyo 2040, which aims to promote the realization of three visions of "New Tokyo": "Safe City," "Colorful City," and "Smart City."

China has made significant strides in promoting the development of VICAD technology and industry. The country has implemented a systematic approach, from top-level design to strategic layout, industry application, and other levels, resulting in the industry reaching a global leading level. In terms of technical route and policy system, China has adopted the "automated driving + connected empowerment" route, which has become a broad consensus in autonomous driving technology. Government authorities have actively strengthened the top-level standard design and created a favorable environment for industrial development by issuing a series of policy documents, including the Outline for the Strategic Plan to Expand Domestic Demand (2022-2035)[9] , Strategies for the Innovative Development of Intelligent Vehicles[10], Development Plan for the New Energy Vehicle Industry (2021-2035)[11], Program of Building National Strength in Transportation[12] , and Outline of Medium and Long-term Development Plan for Scientific and Technological Innovation in the Transportation Field (2021-2035)[13]. These policies have provided direction for the development of vehicle-infrastructure cooperated autonomous driving. Local government sectors have also played a significant role in promoting industrial development by issuing guidance and development plans that combine their own development needs and advantages. They have vigorously developed vehicle-infrastructure cooperated technology and facilitated industrial applications. In terms of technology verification and application demonstration, the Ministry of Industry and Information Technology has taken the lead in approving the construction of several national-level Vehicle to Everything pilot areas, including Jiangsu (Wuxi), Tianjin (Xiqing), Hunan (Changsha), and Chongqing (Liangjiang New District). The ministry has also supported the construction of the Vehicle to Everything demonstration area and the pilot project of "Dual Intelligence"[14] in Beijing, Shanghai, Guangzhou, Shenzhen, and other places, to speed up the large-scale construction and deployment of vehicle-infrastructure coordination infrastructure. Organizations such as the IMT-2020 (5G) Promotion Group and China Intelligent Connected Vehicle Industry Innovation Alliance (CAICV) have launched several large-scale pilot application demonstration activities, including “Three-Layers”, “Four-Layers” and the “New Four-Layers” Interoperability V2X Application Demonstration

The research and exploration of VICAD remains an active area of investigation within the industry. To accelerate the establishment and refinement of the VICAD theoretical and technical system, and to advance its implementation and application, Ya-Qin Zhang, the academician of Institute for AI Industry Research (AIR), Tsinghua University,

9. On December 14, 2022, the Central Committee of the Communist Party of China and the State Council issued the Outline for the Strategic Plan to Expand Domestic Demand (2022-2035)
10. On February 10, 2020, 11 departments including the National Development and Reform Commission jointly released the Strategies for the Innovative Development of Intelligent Vehicles
11. On October 20, 2020, the General Office of the State Council issued the Development Plan for the New Energy Vehicle Industry (2021-2035)
12. On September 19, 2019, the Central Committee of the Communist Party of China and the State Council issued the Program of Building National Strength in Transportation

and more than 10 industry units, including Baidu Apollo, China Academy of Information and Communications Technology, China Information and Communication Technology Group Co., Ltd., and China Unicom, jointly established a research team. Our team engaged in systematic research and exploration of VICAD. In 2021, we proposed the VICAD technical route, which addressed issues arising in the development of autonomous driving. From a perspective of safety, operational design domain (ODD)[15] , and economy, we analyzed and demonstrated VICAD's efficacy. Our team also identified a weakness in the "infrastructure" aspect of VICAD, and therefore, proposed classification standards for intelligent roads and a development plan to coordinate the construction of high-level intelligent roads. In June 2021, the white paper, Key Technologies and Developing Prospect of Vehicle Infrastructure Cooperated Autonomous Driving 1.0, was published. It was the first of its kind for the industry, and provided valuable insights into the future of VICAD.

In 2022, our focus remained on VICAD, with increased R&D efforts and a better understanding of the technology and overall system.

Firstly, VICAD is a continuously developing technology system that needs to meet the integrated development needs of various cross-industry sectors, such as autonomous driving, intelligent transportation, C-V2X Vehicle to Everything, and shared travel. To achieve this, we must construct a "future-oriented and adaptable to the present" vehicle-infrastructure cooperative system. This will support the widespread adoption and implementation of both "progressive" and "leapfrogging" autonomous driving routes, while also laying a strong foundation for the future promotion of intelligent transportation, smart travel, and smart city integration and innovation.

Secondly, we have clarified the implementation path of VICAD towards large-scale commercialization for autonomous vehicles at different levels. With the help of the all-round technical capabilities of vehicle-infrastructure cooperation (including VIC perception, VIC decision-making and planning, and VIC control), the bottleneck problems faced by autonomous driving can be substantially solved to improve the level and capability of autonomous driving.

Thirdly, the primary task of developing VICAD at this stage is still to make up for the shortcomings of "infrastructure". China has strong institutional mechanisms, strategic policies, industrial ecology, and technological leadership. Therefore, it is necessary to make overall planning and promote the construction and deployment of high-level intelligent roads in leading cities and expressways by levels, to explore a series of new commercial operation patterns, such as vehicle-infrastructure cooperated bus transit lanes and vehicle-infrastructure cooperated autonomous driving lanes. In this way, practical experience can be accumulated, and mature solutions can be developed, promoted and reproduced.

Finally, through the construction and development of high-level intelligent roads, favorable

13. On January 24, 2022, the Ministry of Transport and the Ministry of Science and Technology issued the Outline of Medium and Long-term Development Plan for Scientific and Technological Innovation in the Transportation Field (2021-2035)
14. The pilot project for the coordinated development of smart city infrastructure and intelligent connected vehicles is referred to as the "Dual Intelligence" pilot project
15. Quoted from the Taxonomy of Driving Automation for Vehicles (GB/T 40429-2021).The Taxonomy of Driving Automation for Vehicles (GB/T 40429-2021).

economic and social benefits can be produced. The "critical issue" of autonomous driving development can be resolved, and accident risks can be significantly reduced, thus improving traffic operation efficiency, driving local and regional economic development, and bringing a sense of safety, gain, and happiness to the people.

After an extensive research effort spanning over a year, we are proud to present our white paper titled "Key Technologies and Developing Prospect of Vehicle Infrastructure Cooperated Autonomous Driving 2.0." This paper is structured into seven chapters, each of which serves a specific purpose and contributes to the overarching goals of the paper.
Chapter 1 provides an overview of the current state of autonomous driving, highlighting its development status and outstanding issues that need to be addressed.

Chapter 2 defines the concept of Vehicle Infrastructure Cooperated Autonomous Driving (VICAD), its connotation and extension, development stage, status, and future trends.

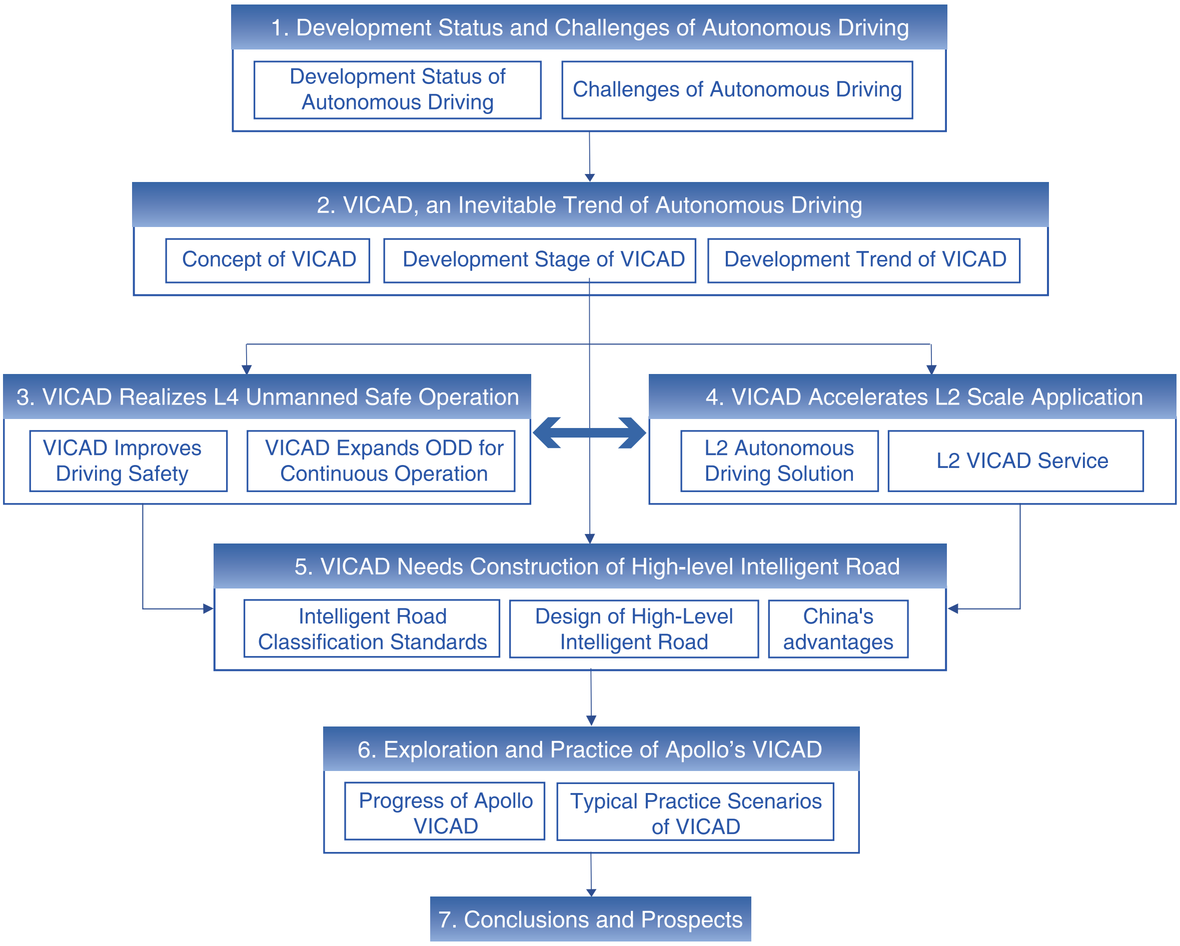
Chapter 3 presents a comprehensive solution to the problems faced by L4-level autonomous driving and unmanned operation through the use of VICAD. It aims to achieve zero intervention, high safety, and a driving capacity that surpasses human abilities. The ultimate goal is to enable unmanned and safe operation of L4-level autonomous driving.

Chapter 4 discusses the various application services that can be provided for vehicles and drivers through VICAD. It highlights how L2 autonomous vehicles can travel smoothly in cities, expressways, and other traffic environments.

Chapter 5 proposes intelligent classification standards for roads and an overall design plan for high-level intelligent roads. It also suggests a step-by-step approach to the construction of such roads and conducts a quantitative analysis of the economic and social benefits that can be derived from their construction.

Chapter 6 introduces the latest exploration and practice of Baidu Apollo and AIR of Tsinghua University in terms of vehicle-infrastructure cooperation in the past two years.

Finally, Chapter 7 summarizes the core viewpoints and development suggestions, tying together the various concepts presented throughout the paper.



This white paper still requires continuous revision and refinement. We express our sincere gratitude to the units responsible for its preparation, personnel involved, and guiding experts for their efforts in conducting the research and preparation of this paper. We also extend a warm welcome to experts and colleagues in the industry to provide their valuable guidance and suggestions. We believe that collaboration among us will contribute to the technical research and industrial promotion of vehicle-infrastructure coordination, accelerating the innovative development of China's autonomous driving and intelligent transportation integration.

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Development Status and Challenges of Autonomous Driving

Autonomous driving has long been a human inspiration and aspiration. In 1925, the world's first radio-controlled car appeared on the streets of New York, and it would be the earliest prototype of autonomous driving; in 1961, the Stanford Cart, which was produced by the Stanford University Research Institute, relied on the roof-mounted camera and computational and control algorithms to realize perception, planning and control of vehicles. In the past decade, new technological advances such as new sensors, deep learning algorithms, IoT, silicon technologies, cloud computing, high-definition mapping are making true autonomous driving autonomous driving realistic and possible for the first time. Autonomous driving has become the most critical force in driving the transformation of the new automotive industry.

1.1
Development Status of Autonomous Driving

In recent years, the field of autonomous driving has undergone significant development, transitioning from the stage of technology research and verification to the stage of product implementation. A growing number of companies are now actively engaged in the research, development, and manufacturing of autonomous vehicles, collaborating to explore the implementation and application of autonomous driving. According to the Society of Automotive Engineers (SAE) and China's autonomous driving classification standard15, autonomous driving is classified into 6 levels, ranking from L0-L5[16] . The standard is based on whether the driver needs to be in a driving state after the autonomous driving function is activated, L3 is used as the dividing line for the autonomous driving. In theory, the function above L3, including L3, can only be called the high-level autonomous driving, while those below are referred to as assisted driving. The ultimate goal of autonomous driving is L5, which refers to fully autonomous driving, allowing the vehicle to perform complete dynamic driving tasks and offer support in all road conditions, without any driver intervention. The autonomous vehicle at such level can be also called a driverless car.

Currently, L2 assisted driving vehicles with advanced driver assistance systems (ADAS) represent the main force in the market and are in the stage of accelerated mass production. However, their market penetration rate and application scale still need to be increased further. L3 and higher autonomous driving technology are still in the stage of test verification and regional demonstration. Some enterprises have started to enter the stage of small-scale fully unmanned open operation of autonomous driving, but challenges such as technology, infrastructure, regulations, and others still need to be overcome for city-level global commercialization

(1) Most Car Manufacturers Achieve Mass Production of L2 Assisted Driving Vehicles, Significantly Increasing Market Penetration Rate.

Currently, the primary focus in the automobile industry is on the mass production of L2-level autonomous vehicles. Companies such as Tesla are proposing to advance this technology to L2.5 or even close to L3 systems, based on the standard L2-level driver assistance system. According to statistics as of June 2022[17] , the cumulative sales of passenger cars in China from January to June reached 10.355 million units, of which the sales of L2 and above level intelligent connected vehicles (ICVs) were 1.873 million units, with a penetration rate of 20.2%. The cumulative sales of new energy passenger vehicles from January to June nationwide were 2.60 million, including the 1,123,000 new energy intelligent connected vehicles of L2 and above, with a penetration rate up to 43.2%. The China Automotive Industry Association predicts that the sales of intelligent connected vehicles of L2 and above will reach 4.6 million, while the sales of new energy vehicles in 2022 are expected to

16. The Taxonomy of Driving Automation for Vehicles (GB/T 40429-2021).
17. L0: emergency assistance, L1: partial driver assistance, L2: combined driver assistance, L3: conditional autonomous driving, L4: highly autonomous driving, L5: fully autonomous driving.

reach 5.5 million, and the sales of new-energy intelligent connected vehicles are expected to reach 2,376,000.

(2) Rapid Expansion of High-Level Autonomous Driving Application Scenarios and Initial Commercialization Achieved[18]**.**

Currently, autonomous driving technology is not yet capable of achieving fully autonomous driving in any scenario. Continuous learning and feedback are required to achieve sustained iterations of technological capabilities. Priority is given to landing in areas and environments where there is less mixed traffic, reasonable traffic light settings, and a strong awareness of traffic rules, such as high-speed roads, trunk logistics, ports, parks, and fixed routes. These include scenarios such as connecting shuttle buses, cleaning vehicles, and autonomous taxis.

1. In terms of Robotaxis. According to "China Autonomous Driving Market and Future Mobility Market Outlook" published by IHS Markit, Robotaxis will account for more than 60% of the shared travel market in the future. Baidu's autonomous driving travel platform "Apollo Go" has provided autonomous driving travel services in more than 10 cities such as Beijing, Shanghai, Guangzhou, Shenzhen, and Chengdu, with a cumulative order volume exceeding 1.4 million[19] . Globally, companies such as GM Cruise and Waymo are also exploring the commercial operation of autonomous taxis.

2. In terms of trunk line logistics. Autonomous driving can fill the gap of over 10 million truck drivers in China and save 30% to 40% of labor costs in total transportation costs. There are many autonomous driving companies in this field, including DeepWay, Mainline Technologies, Yuncore Technologies, QianGua Technologies, and Xidi Zhijia.

3. In terms of unmanned delivery. During the COVID-19 pandemic, unmanned delivery replaced manual delivery to complete tasks such as delivering meals, medicines, express delivery, and cleaning, making positive contributions to epidemic prevention. In the next 5-10 years, unmanned delivery will enter a period of rapid development and become an important component of smart logistics. Domestic unmanned delivery already has a relatively complete industrial chain, such as JD.com, Meituan, and Cainiao.

4. In terms of unmanned mining trucks, closed park logistics, and other areas with simple scenes and few interfering factors. Unmanned autonomous driving services can be provided in specific environments such as ports, mining areas, and airports, improving the efficiency of automated operations.

In addition to the above mainstream autonomous driving application scenarios, there are many other autonomous driving sub-application scenarios that remain to be explored.

18. China Automotive Industry Association: Automobile Production and Sales Report for the First Half of 2022 in China
19. By the end of the third quarter of 2022, the total number of riding services provided by Apollo Go to the public has reached 1.4 million

1.2
Challenges of Autonomous Driving

Autonomous driving is a multifaceted system comprised of a comprehensive array of autonomous driving hardware (laser radar, millimeter wave radar, camera, ultrasonic sensor, GPS positioning device, chip and computing platform, etc.) and multiple complex systems (HD map system, high-accuracy positioning system, perception system, decision planning system, vehicle control system, vehicle communication system, etc.). Despite notable progress in current autonomous driving technology and the initial realization of autonomous driving commercialization, there remain significant obstacles to be surmounted before achieving widespread acceptance and adoption. The principal determinants that influence the commercialization of autonomous driving can be distilled into three primary factors: safety, operational design domain (ODD), and economy.

(1) Challenges to Achieving Safe Autonomous Driving: Risks of Failure in Specific Scenarios Remain a Concern

Safety issues remains the most critical factor affecting the commercialization of autonomous driving, and the safety challenges faced by autonomous vehicles differ at various levels of automation.

In terms of low-level autonomous driving, driver assistance systems are limited in their functionality and are susceptible to inadequate coping capacity and failure in specific scenarios. For instance, the automatic emergency braking system may not be able to cope effectively in scenarios such as low light conditions or where children are crossing the road, increasing the risk of collisions. Additionally, special target recognition scenarios, such as pedestrians holding umbrellas or wearing raincoats in rainy weather, and high-accuracy positioning scenarios, such as tunnels and urban bridges, are also prone to system failure. Through the study of a number of safety accident cases of autonomous driving, both domestic and international, it is found that there are certain difficulties in the accurate recognition of stationary traffic facilities and stationary traffic participants and real-time intervention and control by vehicles, constituting the main cause of accidents.

In terms of high-level autonomous driving, the most significant challenge is achieving full "unmanned" operation. At levels L4-L5, where the driving and liability subject are switched from the driver to the autonomous driving system, it is essential to achieve a success rate of 99.9999% or higher to guarantee extremely low probability of collision accidents. According to the California Department of Motor Vehicles (CA DMV) statistics, as of November 30, 2021, 28 autonomous driving companies have completed over 4.1 million miles of testing with 1,180 autonomous vehicles. Waymo's 693 registered vehicles had an annual mileage of over 2.32 million miles with a total of 292 takeovers and an average takeover mileage of 7965 miles. In terms of accidents, Waymo reported a total of 64 traffic accidents, with an average of 27.6 accidents per million miles, which is equivalent to 171.5×10-7 times/km. In contrast, Cruise had 30 traffic accidents with an average of 34.1 accidents per million miles (total mileage of autonomous driving in 2021: 876,000 miles), resulting in an accident probability of 211.9×10-7 times/km, which is significantly higher than the accident probability of human driving[20] . These statistics indicate that there is still a gap between autonomous driving and the ultimate goal of "absolute safety" and fully "unmanned" operation.

(2) Prominent Issues Such as Long-Tail Perception, Mixed Traffic Scenarios, and Extreme Scenarios are Limiting Vehicles' ODD

Autonomous driving is a complex system that is heavily dependent on the external environmental conditions under which it operates, also known as the Operational Design Domain (ODD). The ODD encompasses various factors such as geography, traffic flow, road features, and time limit, among others. However, the ODD of autonomous driving is restricted by a series of challenges that are difficult to overcome. These challenges include the perception long tail, mixed traffic scenarios, and extreme scenarios, which all pose significant limitations to the ODD of autonomous vehicles.

The ODD (Operational Design Domain) of autonomous driving pertains to the external environmental conditions that enable its functional operation as determined during the design of the autonomous driving system. These conditions include the environment, geography, time limits, traffic flow, road features, and more. Several factors restrict the ODD of autonomous driving, such as: 1) road conditions, expressways, intersections without traffic lights, mountain roads, etc.; 2) environmental conditions, weather (such as rain, snow and fog), sunshine conditions (day or night, backlight and tunnel entrance), etc.; 3) other conditions include the outdated map information, toll gates, puddles, low-hanging plants, icy roads, scattered objects, special machinery, and human behavior that violates traffic rules.

While restricting ODD is vital to ensuring vehicle safety, it is not conducive to the continuous operation of autonomous driving. Currently, autonomous vehicles can only drive in a limited environment due to the absence of national autonomous driving regulations issued by the United States Congress, and requirements from local governments such as Arizona and Florida, which mandate driving testing and trial operation of self-driving cars in limited areas. Furthermore, the currently mass-produced L2 autonomous vehicles can only enable their autonomous driving system in expressways, freeways, or limited environments in some cities.

The primary reason for restricting ODD is that autonomous driving faces several challenges, such as perception long-tail, mixed traffic scenarios, and extreme scenarios that are difficult to overcome, and cannot guarantee successful responses in all scenarios. Data-driven deep learning technology has been widely used in the field of autonomous driving

20. Based on the data in the report "Analysis of Motor Vehicle Ownership and Usage Characteristics in Beijing" released by the Beijing Transportation Development Research Institute in 2018: The number of motor vehicles in Beijing was 6.084 million, and the average car usage rate was 67.6 %, the average daily mileage of a car was 31.3 kilometers, and the number of traffic accidents announced in Beijing in 2018 was 3,242. It is estimated that the accident probability of a manned car is about 0.69×10-7 times/km. SAE J3016-2021 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles

perception, and single-vehicle autonomous driving has been achieved in daily driving environments. However, due to restrictions from the physical characteristics of vehicle-side sensors and computing power, the perception capacity in long-tail scenarios, such as bad weather, scattered objects, and blind zones, still requires continuous improvement.

In these scenarios, the infrastructure can leverage its stability, globality, and other advantages to provide high-performance traffic signal data and full perception data to strongly support single-vehicle intelligent autonomous driving systems, thus reducing ODD restrictions caused by inadequate perception capacity. In addition to perception, single-vehicle intelligent autonomous vehicles face challenges such as mixed traffic scenarios. From the perspective of the overall traffic situation, relying on individual intelligence alone is insufficient to achieve optimal results. Thus, unified and coordinated management of vehicles and infrastructures is necessary to balance the safety and efficiency of autonomous vehicles.

(3) Autonomous Driving Needs More Competitive Costs.

The automobile industry demands rigorous development processes, including extended testing and optimization phases, and thorough performance evaluations under various extreme conditions prior to delivery to consumers. The mechanical, electronic, and electrical components of the vehicle must perform optimally to ensure driver safety. Autonomous vehicles, in particular, require the highest levels of safety and stability, which impose more stringent requirements than conventional vehicles. This necessitates additional sensors, auxiliary positioning equipment, and communication equipment. The mass production of these components, sensors, computing platforms, and supporting software and hardware equipment significantly increases the cost of the vehicle, rendering mass production a challenging task.

To achieve the large-scale commercialization of autonomous driving and establish a healthy commercial ecosystem, cost reduction is crucial. Currently, the prices of self-driving car hardware such as laser radars and chips are decreasing. This is the result of the collective efforts of the industry chain, especially domestic companies. For instance, the Baidu and ARCFOX collaboration, Apollo Moon, has reduced costs to 480,000 yuan, while the sixth-generation unmanned vehicle, Apollo RT6, launched by Baidu in July 2022, has reduced costs to 250,000 yuan and improved performance substantially, marking the actualization of mass production of L4.

To further decrease costs, continuous independent research and development of software and hardware integration, as well as optimization of design, manufacturing, production management, and quality control processes, are imperative to promote mass production and application of autonomous driving. The economies of scale become more apparent as the scale of mass production increases, leading to lower costs.

In summary, under certain conditions of autonomous driving capability, safety, operational design domain (ODD), and economy are conflicting factors. For instance, to enhance autonomous driving safety, ODD must be limited, and adjustments must be made to approach the system's upper limit, allowing for small-scale commercialization and implementation. Alternatively, expensive equipment can be used to enhance the safety of single-vehicle intelligent autonomous driving, but at the expense of economy. To achieve large-scale commercialization, balancing the requirements of safety, ODD limitations, and economy is necessary to enhance the level and capability of autonomous driving fundamentally.

02

VICAD, an Inevitable Trend of Autonomous Driving

The notion of vehicle-infrastructure cooperation is not a new concept. As early as the 1960s, General Motors, one of the prominent American automobile giants, constructed an electronic highway test track located in Princeton, New Jersey. This experimental track facilitated the automatic startup, acceleration, steering, and stopping of vehicles, obviating the need for manual intervention throughout the process, which is considered to be the earliest instance of "vehicle-infrastructure cooperation" in the industry.

Following this pioneering feat, the municipal government of Princeton published a comprehensive article outlining the prospective landscape of autonomous driving. Envisioned in this vision was a future in which individuals would be able to engage in leisure activities such as playing bridge or taking a nap while traveling on weekends, with the advent of electronic highways. Regrettably, due to technological limitations and high costs, this project came to a halt before its full potential could be realized.

2.1
Concept of VICAD

VICAD is an advanced system that seamlessly integrates intelligent autonomous driving technology, C-V2X, and 4G/5G communication technologies, along with the "person-vehicle-infrastructure-cloud" traffic elements. This integration provides an all-round cooperation between the vehicle and various traffic elements, enabling cooperative perception, decision-making, and planning, as well as cooperative control. VICAD utilizes various communication modes, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N), and vehicle-to-person (V2P) communications to facilitate efficient communication between the vehicle and other traffic elements. Specifically, V2I communication encompasses the integration of various road systems and equipment facilities such as sensing facilities, weather detectors, state monitoring equipment, and traffic guidance and control facilities. V2N communication involves the integration of map platform, traffic management platform, travel service platform, and so on. The overarching objective of VICAD is to cater to the diverse application requirements of autonomous driving vehicles at different levels, ranging from aided driving to high-level autonomous driving. Through this, VICAD enables the achievement of the developmental goals of autonomous driving optimization and overall traffic optimization. Figure 2.1 illustrates the cooperative relationship between autonomous vehicles and different traffic elements.

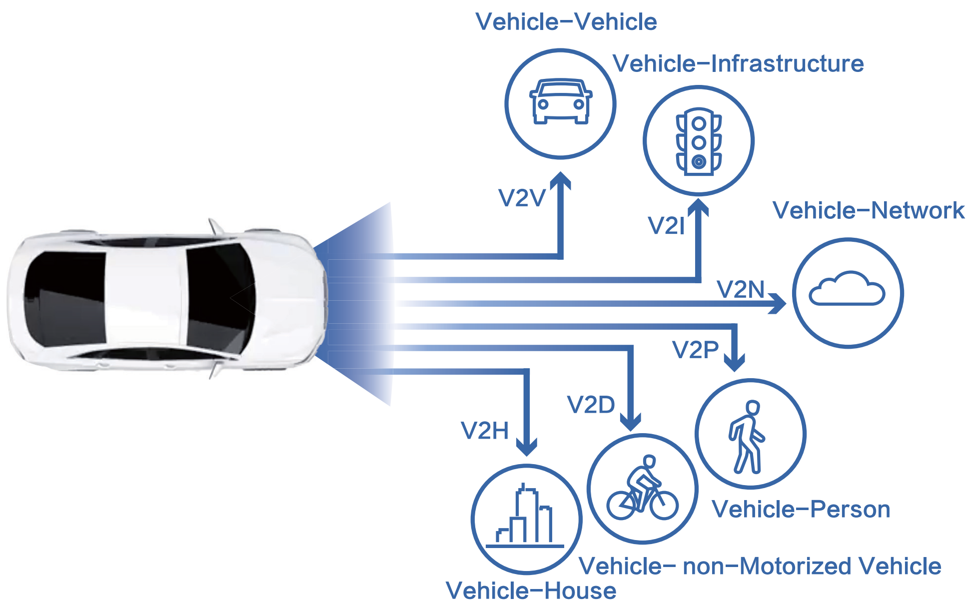


Figure 2.1 cooperative Relationship between Autonomous Vehicles and Different Traffic Elements

In addition to autonomous driving technology, the development of VICAD demands the comprehensive application of various fundamental support technologies. These technologies include:

1) Highly reliable, low-latency communication technology, which includes wireless communication and wired transmission. Direct wireless communication (e.g., LTE-V2X PC5, NR-V2X PC5) and cellular mobile communication (including 4G, 5G, and the future 6G) are examples of wireless communication. Wired transmission includes CAN, vehicle Ethernet, and optical fiber network.

2) 2D/3D high-precision fusion sensing technology, which encompasses sensor offline/online high-precision calibration technology, multi-sensor fusion technology, traffic event perception and cognition technology, traffic participant behavior prediction technology, and traffic operation status detection and prediction technology.

3) HD map and high-accuracy positioning technology, which comprises HD map dynamic updating technology and roadside auxiliary positioning technology.

4) Vehicle-infrastructure cooperative decision-making and cooperative control technology, which includes autonomous driving intention prediction, game arbitration, guidance scheduling, and other cooperative decision-making and planning. It also covers multi-objective cooperative control technology for vehicles, facilities, and people.

5) High-performance cloud computing technology, which includes high-performance edge computing technology, multi-level cloud control platform technology, big data and artificial intelligence platform technology, and intelligent scheduling technology that integrates computing and network.

6) Multi-level in-depth security technology, which includes autonomous driving functional safety and expected functional safety, information security technology (including data security, network security technology, geographic information security, etc.), unified security authentication technology, security situation awareness technology, security active defense technology, etc.

VICAD, is an advanced technology that aims to ensure vehicle safety from a holistic perspective. The central goal of VICAD is to establish a "sky eye" for each vehicle, allowing efficient allocation of road time and space resources while making full use of all traffic elements. To achieve this, VICAD requires the construction of a set of closed loop empowerment systems that connect the cyber and physical spaces, integrating various advanced technologies such as perception, computing, communication, decision-making, and control. This integration leads to state awareness, real-time interaction, scientific decision-making, and precise execution based on the free flow of data.

The "V" in VICAD pertains to vehicles, including those with various connected levels and automation; while the "I" signifies infrastructure, which primarily refers to roadside intelligent infrastructure and the environment. The infrastructure encompasses following:

1) Road engineering and supporting auxiliary facilities such as pavement, road signs, traffic lights, lighting, and power supply.

2) Intelligent perception facilities, such as cameras, millimeter wave radar, and lidar are also essential.

3) Vehicle-infrastructure communication facilities, such as direct wireless communication and cellular mobile communication facilities.

4) Computing control facilities, such as roadside edge computing nodes, multi-access edge cloud or cloud service platforms at all levels.

5) HD maps and auxiliary positioning facilities

6) Other ancillary equipment and facilities, such as power supply and lighting facilities.

7) All types of personnel on the road, including pedestrians, construction workers, non-motorized vehicle drivers, etc.

In summary, VICAD is a sophisticated technology that aims to optimize traffic systems by enhancing vehicle safety, reducing congestion, and minimizing environmental impacts. By integrating various advanced technologies, VICAD enables efficient allocation of road time and space resources while making full use of all traffic elements. The implementation of VICAD requires the construction of intelligent roadside infrastructure and environments, as well as the integration of different technologies to enable precise execution based on the free flow of data.

A novel and intricate system that encompasses all the necessary components for supporting VICAD is referred to as a Vehicle-Infrastructure Cooperated System (VICS). This system is distinguished by its inherent features, such as data-driven, software-defined, ubiquitous connectivity, virtual-real mapping, and heterogeneous integration, and it is also oriented towards autonomous driving and intelligent transportation applications. Additionally, this system offers a set of core features and advantages:

(1) Integration of all transportation elements

As illustrated in Figure 2.2, the traffic participants, transportation tools, traffic infrastructure, and traffic environment in the VICS are no longer viewed as simple objects. Instead, they are considered digital twins with independent identities and information interaction capabilities through the collection and fusion processing of sensors. This approach facilitates the effective transmission of information and decision-making control flows between physical entities and their corresponding digital twins. For example, remote vehicle control, optimal road traffic light control, and road variable sign control can be achieved through this system's closed-loop information transmission and decision-making control. With the global scheduling of the VICS, the complex cyber-physical system fosters a more efficient and orderly traffic operation situation among different physical entities.

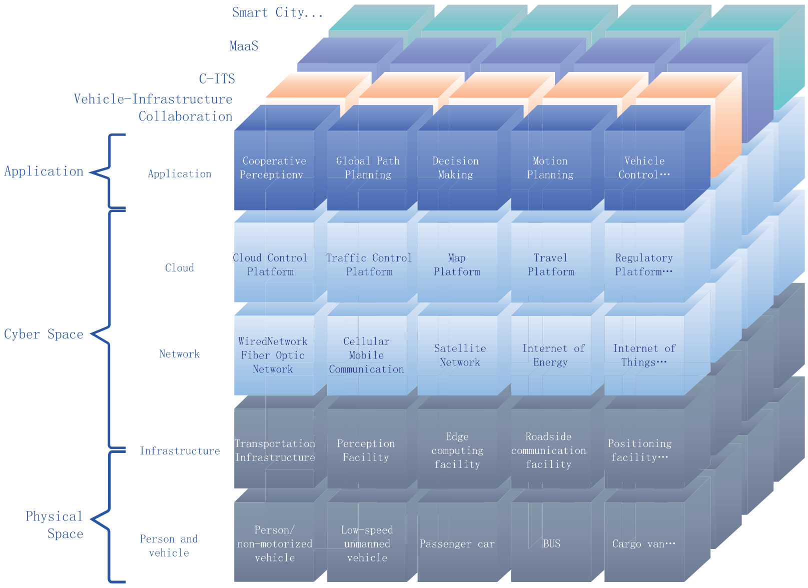


Figure 2.2 VICAD-based Integrated System Model Covering All Transportation Elements

(2) Integration of computing, perception, decision-making, and control for autonomous driving

As illustrated in Figure 2.3, Autonomous Driving (AD) technology empowers vehicles to autonomously complete the "perception-decision-planning-control-execution" process. Conversely, VICAD allows for the distribution of these functions across the vehicle, infrastructure, or cloud, culminating in an integrated perception, decision-making, and control system. The fundamental basis for achieving this integration lies in the utilization of advanced computing and interconnection technologies. The primary application of this technology is in the realm of integrated perception, decision-making, and control.

Since 2019, there has been a swift increase in the computing power of smart vehicles. For instance, the computing power of the TESLA Model 3 has reached 144 TOPS, and NIO's ET7 surpasses 1000 TOPS. However, relying solely on single-vehicle intelligence to enhance perception and improve computing power by increasing sensors and computing units is not economically viable. Addressing this challenge, VICAD employs the transmission and interconnection of low-latency and highly-reliable networks, along with the abundant infrastructure and cloud computing power, to enable effective sharing of vehicle perception capabilities and computing power. This approach facilitates a reasonable distribution and allocation of system-wide computing power.

Regarding integrated perception, decision making, and control, VICAD extends the perception range of autonomous vehicles and enhances their perception capabilities through cooperative perception via vehicle-vehicle, vehicle-infrastructure, and vehicle-cloud interactions. Additionally, integrated decision making and control enable handling of global optimization scenarios and extreme scenarios, enhancing the safety of autonomous driving and broadening the ODD of autonomous vehicles. Moreover, environmental control promotes a secure and orderly driving environment, enhancing the overall safety and efficiency of traffic operations.

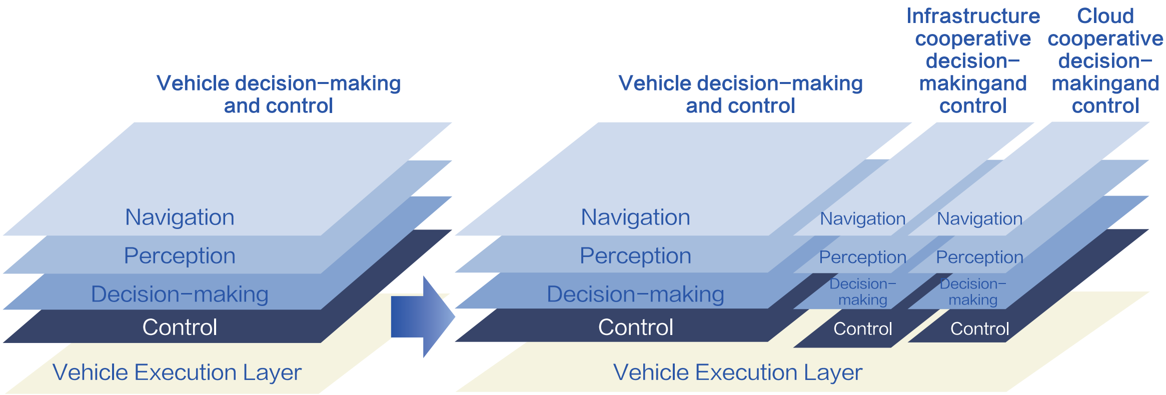


Figure 2.3 Integration of Perception, Decision-making and Control of VICAD

(3) Cross-industry application and integration of data-driven autonomous driving and intelligent transportation

The core goal of the vehicle-infrastructure cooperated system is to use a set of vehicle-infrastructure- cloud and basic capability system, to simultaneously empower autonomous driving, intelligent transportation, and even shared travel, smart cities and other industries through data-driven mode, and to support continuous iteration and innovative development. A large amount of data in conventional transportation systems and vehicles is hidden, and the potential value behind it has not been fully utilized and unearthed. As shown in Figure 2.4, the vehicle-infrastructure cooperated system is able to continuously transform data from the hidden form in physical space to the dominant form in cyber space by building a free-flowing closed-loop empowerment system of "state awareness, real-time analysis, scientific decision-making, and precise execution". Data, the foundation and soul of the vehicle-infrastructure cooperated system, runs through the entire process of state perception, real-time analysis, scientific decision-making, and precise execution. Data is continuously accumulated in the process of automatic generation, automatic transmission, automatic analysis, automatic execution, and continuous iterative optimization, continuously generating optimized data, and causing the qualitative changes through fusion.

The fundamental objective of the VICS is to leverage a comprehensive set of capabilities including vehicle-infrastructure, cloud, and basic systems to enable autonomous driving, intelligent transportation, shared mobility, smart cities, and other industries in a data-driven manner. This system is designed to facilitate continuous innovation and development.

A significant amount of data in traditional transportation systems and vehicles remains hidden, with untapped potential for value creation. Figure 2.4 illustrates how VICS converts data from its latent physical state to its dominant form in cyberspace by creating a closed-loop system that empowers state awareness, real-time analysis, scientific decision-making, and precise execution. The foundation and essence of this system is data, which permeates the entire process of state perception, real-time analysis, scientific decision-making, and precise execution. Data is accumulated continuously through automatic generation, transmission, analysis, execution, and iterative optimization, generating optimized data that undergoes qualitative changes through fusion.

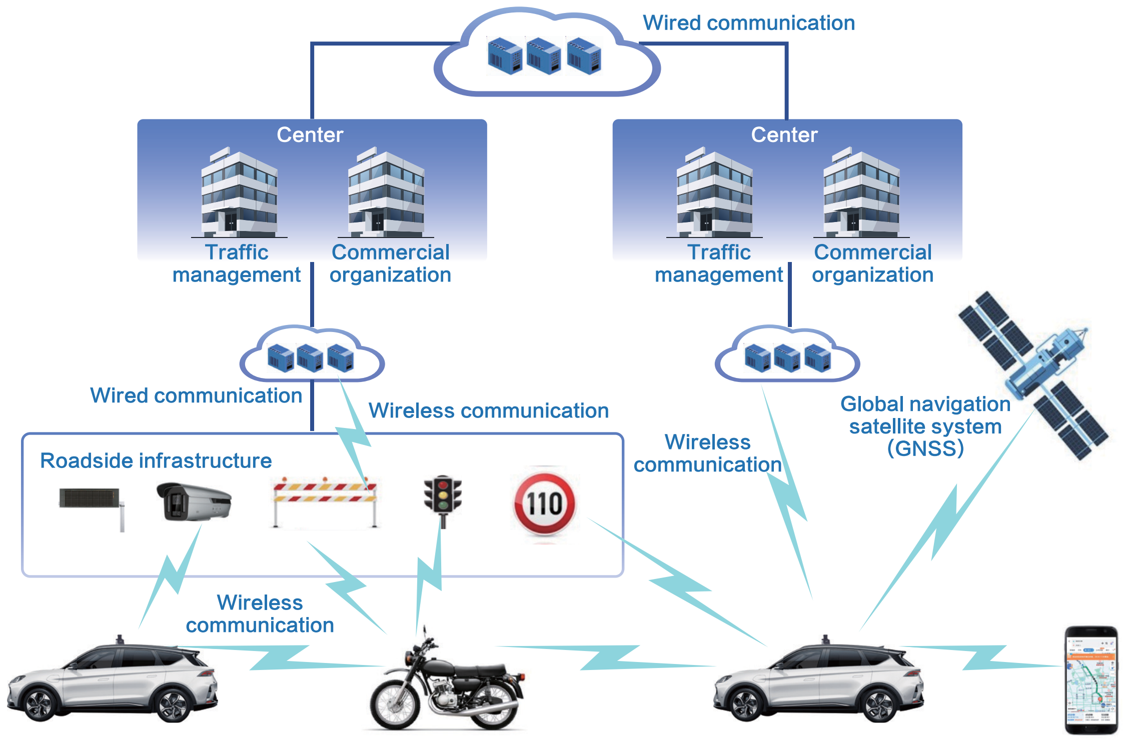


Figure 2.4 Fusion Application of C-ITS and VICAD

2.2

Development Stage of VICAD

VICAD is a complex and dynamic process of gradual evolution from low to high, and its stages are carefully defined in a range of standards and reports issued by various domestic and international agencies, including SAE J3016[21] , SAE J3216[22] and standards issued by domestic institutions[23] . In this white paper, VICAD is divided into three major developmental stages, which are comprehensively outlined in Table 2.1.

1) Stage 1, information interaction and cooperation, is a critical foundation, providing

21. SAE J3016-2021 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles
22. SAE J3216-2021Cooperative Driving Automation: Definitions and Taxonomy
23. The "Development Report on Vehicle-Road Cooperative Autonomous Driving 1.0" released by the Autonomous Driving Committee of China Highway & Transportation Society in June 2019 divides vehicle-road cooperative autonomous driving into four stages: Stage 1: Information exchange and coordination; Stage 2: Perception, prediction and decision-making coordination; Stage 3: Control coordination; Stage IV: Vehicle-road integration. This white paper has made adaptive modifications to the stage division based on the current level of technological development.

interconnection guarantee support for various vehicle-infrastructure cooperative applications;

2) Stage 2, cooperative perception, is the key core to achieve complementary, enhanced, and redundant autonomous driving perception;

3) Stage 3, cooperative decision-making and control, is the ultimate goal, to achieve compatibility and unity between the micro-decision-making control of autonomous driving and the macro-decision-making control of intelligent transportation.

Stage	Sub-stage	Applicable standards	Examples of typical application scenarios
Stage 1: Information Interaction and Collaboration	None	T/CSAE 53-2020	Collision warning, road hazard reminder, etc.
Stage 2: cooperative perception	Stage 2.1: primary cooperative perception	T/CSAE 157-2020	Stage 2.2 necessitates a considerably elevated level of perception compared to Stage 2.1, attaining a full-volume high-precision standard that conforms to the demands of high-level autonomous driving applications. For detailed information regarding relevant performance indicators, refer to Section 5.1.2.
	Stage 2.2: advanced cooperative perception	YD/T 3978-2021[24]	
Stage 3: Cooperative decision-making and control	Stage 3.1: Conditional cooperative decision-making and control	YD/T 3978-2021 T/CSAE 157-2020 T/CSAE 156-2020	Cooperative lane change, coordinated passage without traffic lights, emergency vehicle priority, AVP, etc.
	Stage 3.2: Fully cooperative decision-making and control	None	Remote control driving, optimized control of traffic lights, etc.

Note: High-level Autonomous Driving Data Interaction Content Based on Vehicle-infrastructure Collaboration (YD/T 3978-2021) (or Data Exchange Standard for High level Automated Driving Vehicle Based on Cooperative Intelligent Transportation System (T/CSAE 158-2020))

Cooperative Intelligent Transportation System - Vehicular Communication Application Layer Specification and Data Exchange Standard (T/CSAE 53-2020)

Cooperative Intelligent Transportation System - Vehicular Communication Application Layer Specification and Data Exchange Standard (Phase II) (T/CSAE 157-2020)

General Technical Requirements of Automated Valet Parking Systems (T/CSAE 156-2020)

Table 2.1 VICAD Development Stages

24. High-level Autonomous Driving Data Interaction Content Based on Vehicle-infrastructure Collaboration (YD/T 3978-2021) is the communication industry standard, and Data Exchange Standard for High level Automated Driving Vehicle Based on Cooperative Intelligent Transportation System (T/CSAE 158-2020) is regroup standards issued by the China Society of Automotive Engineering, and industry standards are formulated by the evolution and upgrading of group standards.The DAY I standard includes YD/T 3709 and T/CSAE 53, the DAY II standard includes T/CSAE 157, the enhanced V2X

During the first stage of VICAD, direct wireless communication utilizing LTE-V2X technology was utilized to support communication between vehicles and infrastructures, as well as among vehicles themselves. This enabled basic message reminders and safety warning applications.

The second stage of VICAD is centered around the efficient C-V2X vehicle-infrastructure-cloud communication and infrastructure perception technology, which leverages artificial intelligence (AI) and edge computing applications. These technologies enable the utilization of roadside perspective, while also providing the advantage of easy deployment. By addressing issues such as AV occlusion, blind spots, unfavorable lighting, and extreme weather-related perception, the perception range of AV can be expanded, thus enhancing their perception ability and ensuring safe and efficient driving. T
he third stage of VICAD builds upon the foundation of vehicle-infrastructure cooperative perception. By leveraging the ubiquitous interconnected infrastructure and the combined advantages of infrastructure and cloud, applications such as cooperative decision-making and cooperative control can be supported, thereby ensuring the safe and continuous operation of autonomous driving.

2.3
Development Trend of VICAD

2.3.1 Vehicle-Infrastructure Cooperative Perception is Landing

Vehicle-Infrastructure Cooperative Perception has entered the stage of Large-Scale construction, deployment and application. Currently, the first development stage of VICAD has undergone extensive testing and has demonstrated its efficacy through large-scale verification and demonstration applications both domestically and internationally. Additionally, the second stage of VICAD, focused on vehicle-infrastructure cooperative perception, has concluded its theoretical research, technical verification, and standard formulation. It is now accelerating towards large-scale construction deployment and application, which is primarily evident in the following three aspects:

(1) Cooperative perception scenarios: a crucial focus of domestic and international V2X research

Standards related to vehicle-infrastructure cooperation perception in the United States, Europe, and China concentrate on planning numerous application scenarios. Based on DSRC communication technology, the United States was the first to release a series of standards on vehicle-infrastructure cooperation, including SAE 2735, SAE 2945, SAE 3016, SAE 3216, and other related standards. These standards have planned numerous cooperative perception scenarios, such as early warning systems for vulnerable traffic participants, sharing of traffic light information, emergency vehicle warnings, etc. In

Europe, ETSI has developed the European ETSI G5 standard based on DSRC, which is similar to the American standard in terms of scenarios. Furthermore, industry and national standards for DAYI, DAY II, enhanced, and high-level vehicle-infrastructure cooperation application scenarios have been formulated and released[25] . The scenario design of the V2X application layer standard is more comprehensive than that of the United States and Europe, and the service users are designed to consider both L0-L5 ordinary connected cars and high-level autonomous vehicles. Application scenarios involve not only cooperative perception but also cooperative decision making and cooperative control.

(2) Vehicle-infrastructure cooperative perception technology and capabilities have been greatly improved

As the field of vehicle-infrastructure cooperative autonomous driving (VICAD) research progresses, related technologies are gradually advancing, and the perception capabilities of roadside facilities and systems have already satisfied the necessary conditions for delivering scalable application services for different levels of Connected Automated Vehicles (CAVs). For instance, many domestic and foreign automakers such as Ford, Toyota, and Volkswagen have already launched or planned the mass production of commercial models for CAVs of Level 2. Roadside systems can provide basic traffic event and traffic light co-piloted perception services for these vehicles, and can further enable higher complexity applications such as priority passage and green wave traffic control through C-V2X service. Moreover, in the realm of high-level autonomous driving, the perception accuracy, latency, and reliability of roadside systems have already reached the Level 4 vehicle-infrastructure fusion perception standards, enabling closed-loop operation of Level 4 autonomous driving through the sole use of roadside perception capabilities with closed vehicle-end perception. These perception capabilities have been extensively deployed in regions such as Beijing Economic-Technological Development Area and Guangzhou Huangpu District, offering full and high-precision co-piloted perception services for autonomous driving vehicles.

(3) Vehicle-infrastructure cooperative perception technology has been deployed and implemented at the administrative district level in key cities

Cooperative perception between vehicles and roads has emerged as a pivotal direction for the development of vehicle-infrastructure cooperation in recent years. The United States, for instance, has deployed a large-scale system comprising approximately 5,315 Dedicated Short-Range Communication (DSRC) Roadside Units (RSUs) and 18,000 vehicle-mounted On-Board Units (OBUs) at over 350,000 intersections nationwide. Various cooperative perception applications have been implemented in the US, such as construction zone warning, severe weather warning, and blind spot warning, which leverage perception capabilities to improve driving safety. Likewise, traffic light warning and pedestrian crossing warning are examples of cooperative perception scenarios being deployed in demonstration projects in New York City and Tampa. In China, cooperative

25. The DAY I standard includes YD/T 3709 and T/CSAE 53, the DAY II standard includes T/CSAE 157, the enhanced V2X application standard is YD/T 3977, and the high-level autonomous driving V2X application standard is YD/T 3978.

perception is identified as the most crucial application direction in the development of connected vehicle networks, with numerous pilot and demonstration projects being initiated at various levels. Beijing's high-level autonomous driving demonstration zone is an illustrative example, having completed the construction tasks of the 1.0 and 2.0 phases, which support full-precision vehicle-infrastructure cooperative perception applications at 329 intersections. The urban road network boasts a two-way mileage exceeding 750 kilometers, covering a vast area of 60 square kilometers, representing over 70% of the core area of Yizhuang city. The demonstration zone is capable of conducting closed-loop data interaction with hundreds of Level 4 autonomous driving taxis, thereby advancing the development of vehicle-infrastructure cooperation for autonomous driving. As China strives to promote the commercialization of autonomous driving, the 3.0 phase of Beijing's demonstration zone was launched in 2022 to accelerate the construction of larger-scale vehicle-infrastructure cooperation and facilitate the landing of more commercial scenarios[26] .

2.3.2 Vehicle-Infrastructure Cooperative Decision-Making and Control Has Practical Demand

(1) Further Resolving the Safety and ODD Challenges of Automated Driving Through Cooperative Perception

According to the Safety Of The Intended Functionality (SOTIF) theory for expected functional safety of automated driving, there are two ways to improve the safety of autonomous vehicles: one is to transform "unknown" scenarios into "known" scenarios through cooperative perception, and the other is to transform "unsafe" scenarios into "safe" scenarios. Cooperative perception, which provides autonomous vehicles with richer and more accurate perception information through multi-source perception channels, enhances the vehicles' perception abilities and can realize the transformation of "unknown" scenarios into "known" scenarios. However, in terms of transforming "unsafe" scenarios into "safe" scenarios, there are certain limitations that require further resolution through decision making and control. With regard to ODD, cooperative perception can only address some of the limitations of automated driving vehicles. Therefore, there is a need to implement vehicle-infrastructure-cloud cooperative perception, decision-making, and control on a global scale, dynamically manage ODD, and expand autonomous driving ODD appropriately.

(2) Resolving the Conflict between Automated and Non-automated Driving in Mixed Traffic Scenarios

Autonomous vehicles, as a component of the traffic system, coexist with non-autonomous vehicles, lower-level autonomous vehicles, non-motorized vehicles, and pedestrians, along with a significant number of incidents of illegal driving behavior. Therefore, it is urgently necessary to solve the local or global vehicle optimization problem in mixed traffic

26. 2022 Government Work Report by the Beijing Municipal Government.

scenarios, achieve distributed and collective intelligence, and ultimately achieve the goal of global optimization of intelligent transportation development while ensuring traffic safety and efficiency.

(3) Resolving the "Unmanned" Issue in Automated Driving

Automated driving vehicles can be controlled manually by a driver or a safety officer as a safety guarantee in complex or extreme scenarios. However, when L4 vehicles completely remove the driver or safety officer from the vehicle, there remains a probability that single-vehicle capabilities may fail to navigate through complex and extreme scenarios. Therefore, vehicle-infrastructure-cloud cooperative perception, decision making, and control services are needed to provide vehicles with all-encompassing support to ensure the safe navigation of complex and extreme scenarios. This will ultimately enhance the safety and popularity of autonomous driving.

(4) Resolving Traffic Environment Order and Optimization Issues

Cooperative perception in vehicular networks is not only required for automated driving but also widely recognized in the fields of intelligent transportation, shared mobility, and smart cities. China's transportation system has experienced a rapid growth period of nearly 30 years, with the world's largest road mileage and transport scale. However, it still faces many prominent problems, such as the normalization of traffic congestion, a severe traffic safety situation, and the daunting task of achieving carbon neutrality and carbon peak emissions. Vehicle-infrastructure cooperation can support the development of more complex, deeper, larger-scale, and more diverse applications and services, catering to cross-industry, cross-field, and cross-regional traffic needs. Furthermore, it can address crucial concerns, such as regional mobile multi-access, multi-level interoperability and cooperation, large-scale high-density implementation control, high-reliability, and low-latency computing decision-making. By accomplishing individual optimization to group intelligence optimization, substantial changes and breakthroughs for intelligent transportation can be achieved.

03

VICAD Realizes L4 Unmanned Safe Operation

Despite the improving safety and decreasing ODD restrictions of L4 autonomous driving, achieved through the accumulation of testing mileage and continuous technological advancements, the primary objective of L4 autonomous driving development is to achieve fully unmanned driving on a large-scale operational level. This objective necessitates greater emphasis on the safety, availability, and reliability of autonomous driving systems. VICAD has been specifically designed to engage in various L4 autonomous driving processes such as perception, routing, decision making, and control, with the overarching aim of ensuring the safety of autonomous driving within the ODD. In this respect, VICAD surpasses human driving capabilities. Additionally, VICAD can dynamically manage and expand the ODD of autonomous driving, optimize the operating environment, and enable continuous operation without the need for human intervention.

3.1
Service Strategies of VICAD

Building upon the overall architecture of L4 autonomous driving systems, and considering the limited controllability of L4 autonomous vehicles, VICAD can deeply engage in the entire process of perception, decision-making, planning, and control to provide comprehensive support services for L4 autonomous driving (as shown in Figure 3.1). Specifically, Service strategies for L4-based VICAD include the following four aspects:

1. **Addressing the long-tail perception problem of autonomous driving through vehicle-infrastructure cooperative perception:**Leveraging the advantages of vehicle-infrastructure cooperative perception, VICAD collaborates with CAVs to address a series of long-tail perception problems such as ultra-long-distance, blind spots, and occlusions.

2. **Resolving the real-time updating problem of autonomous driving maps through vehicle-infrastructure cooperative perception and dynamic map updating:** Based on vehicle-infrastructure cooperative perception, VICAD can also update the autonomous driving maps on a minute-by-minute basis to help CAVs cope with the problems caused by changes in traffic signs, markings, and traffic lights.

3. **Solving the problems of global path optimization, mixed traffic conflicts, and blockage through vehicle-infrastructure cooperative decision-making and planning:** Through vehicle-infrastructure cooperative routing, VICAD provides global path planning services for CAVs. Through vehicle-infrastructure cooperative decision-making and motion planning, VICAD can also resolve typical mixed traffic scenarios such as traffic congestions.

4. **Addressing complex and special scenarios through vehicle-infrastructure cooperative control:** To address complex and special scenarios of autonomous driving, such as "getting out of trouble" and parking, VICAD can directly control the CAVs to help them successfully deal with these scenarios and reduce safety risks. For complex and unordered traffic environments, VICAD can also effectively intervene and control traffic infrastructure and traffic operations through vehicle-infrastructure cooperative control, optimize the overall traffic environment for autonomous driving, and indirectly control the CAVs, thereby create a safe, simple, and orderly traffic environment for CAVs.

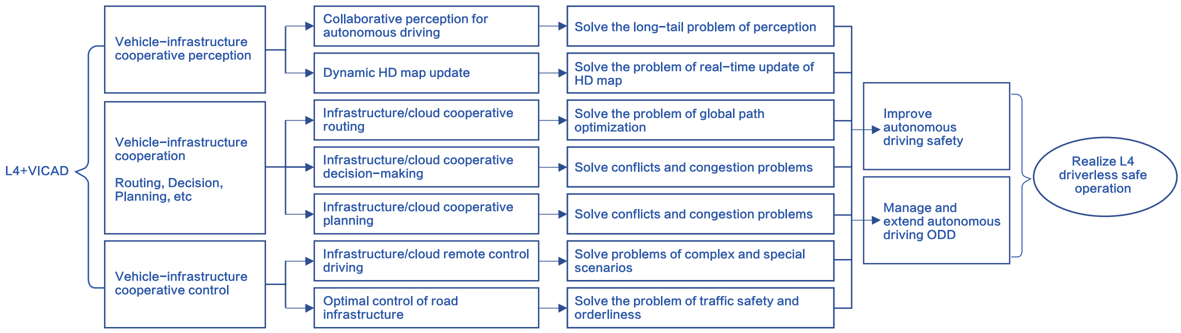


Figure 3.1 L4 Driverless Autonomous Driving Implementation Accelerated by VICAD

VICAD is not designed to substitute the vehicle autonomous driving system completely, but rather to function as an infrastructure-cloud-based autonomous driving system that leverages the advantages of both domains, thereby offering L4 CAV three complementary, redundant and enhanced solutions for support and promotion:

(1) Complementary solution:

One example of how VICAD complements AD is perception. AD has limitations such as restricted sensing range that can be easily blocked by obstacles or affected by environmental conditions and light intensity. Moreover, it has low predictability of other participants' behaviors. In contrast, infrastructure-cloud perception can utilize its wide perception range, that covers a large area of the road network. It can also observe traffic situations continuously over a long period of time with easy engineering. Therefore, it can complement vehicle perception and achieve cooperative perception in scenarios, such as occlusion, beyond visual range, dynamic and static blind spots. This can significantly improve the vehicle's perception capabilities.

Another example is positioning. AV achieves high-accuracy positioning with various methods, but often faces challenges, such as losing positioning signals or inaccurate positioning, in environments, such as long tunnels, undergrounds bridges or tall buildings. To address this issue, perceptual positioning, feature positioning, UWB positioning, C-V2X positioning and other methods are provided by VICAD to realize complementary positioning and assist in high-accuracy positioning.

The third example is infrastructure-cloud cooperative decision making, planning and control. When a single-vehicle intelligent autonomous vehicle (AV) encounters complex traffic environments and driving scenarios, it tends to emergency brake or forced takeover, which may cause safety risks or traffic disruptions. To avoid this situation, VICAD can provide cooperative decision-making and control at the infrastructure or cloud level to replan the path for the vehicle, based on real-time traffic information, global optimization algorithms, conflict resolution strategies etc. This can help the vehicle get through complex scenarios safely. The complementary relationships are illustrated in Figure 3.2.

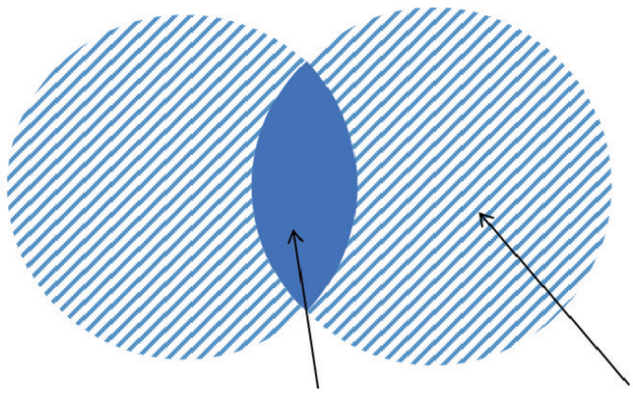


Figure 3.2 Schematic Diagram of Complementary and Redundant Functions of Perception Positioning

(2) Redundant solution:

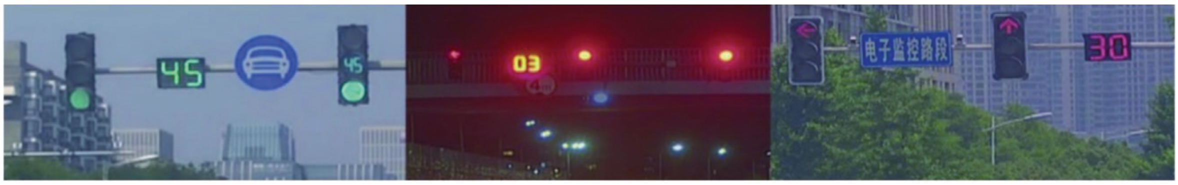
An example of how VICAD provides redundancy for AD is perception and positioning. When the vehicle drives in an open environment it can perceive and locate itself using its own sensors. However, the infrastructure system also detects, identifies and locates the surrounding environment simultaneously or assists the vehicle in fusion positioning by forwarding the positioning information of RTK. In this case, the system acts as a backup for the vehicle in case of sensor failure or signal loss. The redundant relationships are shown in Figure 3.2.

(3) Enhanced solution:

Figures 3.3 and 3.4 illustrate how VICAD enhances AD in traffic signal recognition. In AD mode, the vehicle uses its optical sensor to identify the color of the traffic light in the 3D space and to predict its phase change. However, this mode may encounter various perception problems in different scenarios, such as glare, taillight and neon interference, LED strobe, delayed light brightness compliance, damage and aging, displacement of mobile traffic lights, shaking of European and American suspension lights, multi-phase matching, beyond visual range, blind spots, dynamic and static occlusion, and abnormal weather. In VICAD mode, the vehicle can communicate with low-complexity signal controllers through infrastructure systems or facilities, to obtain accurate reliable semantic information about the traffic light status through low-bit-rate encoding in real time. It can also collect countdown information about light status beyond visual range. In this case, the infrastructure and the cloud play a role in enhancing and improving the recognition capacity.

Multi-semantic traffic lights and multi-color traffic lights

Mobile traffic lights



Countdown traffic lights

Figure 3.3 Different Traffic lights on the Road

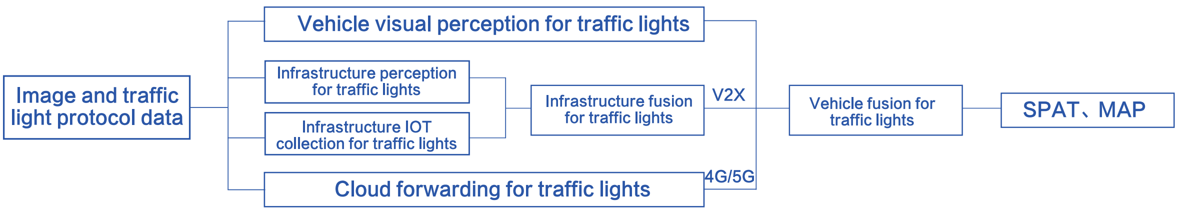


Figure 3.4 Schematic Diagram of Traffic light Perception Enhanced by VICAD

3.2

VICAD Improves Driving Safety

Safety is the fundamental requirement for autonomous driving development and the primary concern at this stage. According to SOTIF theory of autonomous driving, Figure 3.5 shows that autonomous driving operating scenarios can be generally divided into four categories: known safe scenario (Area 1), known unsafe scenario (Area 2), unknown unsafe scenario (Area 3), and unknown safe scenario (Area 4). The core goal of VICAD for autonomous driving safety is to transform "Unknown" scenarios into "Known" scenarios, and "Unsafe" scenarios into "Safe" scenarios. To achieve this goal, VICAD focuses on solving scenario problems in Areas 2 and 3, by transforming Area 2 into Area 1, and proving that residual risk in Area 2 is low; VICAD also converts unknown unsafe Area 3 into Area 1 2 or 4, by minimizing scenarios in Area 3, and ensuring that risk in Area 3 is controlled at a reasonable acceptable level.

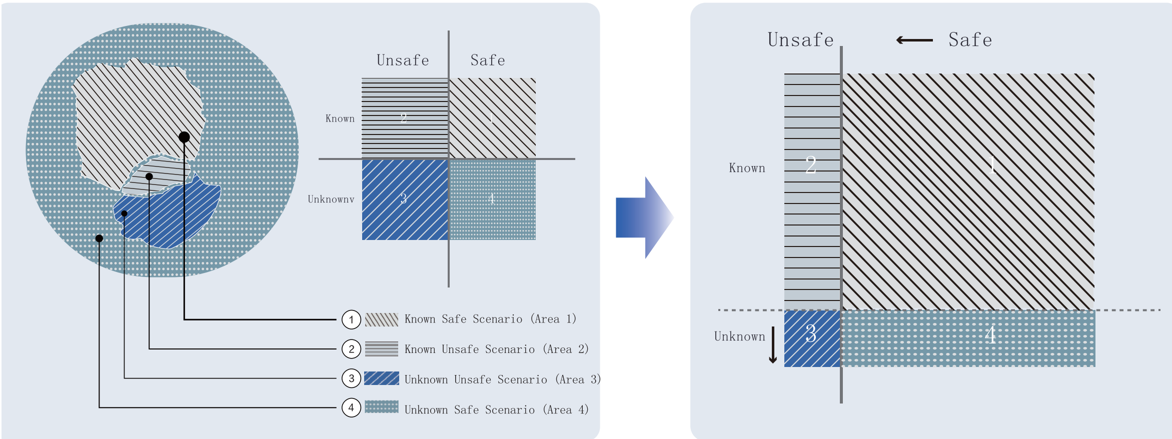


Figure 3.5 SOTIF Safety Goals for Autonomous Driving

3.2.1 Transforming "Unknown" scenarios into "Known" scenarios

Exploring SOTIF "unknown" scenarios is an industry challenge, because "It is difficult to know what is unknown". VICAD leverages the advantages of vehicle infrastructure and cloud cooperative perception, to improve the system's cognitive competence through continuous data-driven and algorithmic learning. It identifies unknown scenarios and transforms them into known scenarios through vehicle-infrastructure cooperative perception, real-time update of HD maps etc. This reduces the safety risk of autonomous driving.

3.2.1.1 Transforming "Unknown" into "Known" with vehicle-infrastructure cooperative perception and positioning

(I) Overall Principle

The vehicle-infrastructure cooperative system comprises the vehicle, infrastructure, and cloud, each endowed with the ability to perceive the surrounding environment, thereby serving as potential sources of perception information for the host vehicle. Figure 3.6 depicts the exchange of perception information among vehicles in the vicinity of the host vehicle via vehicle-to-vehicle (V2V) communication, infrastructure perception system, and facilities through vehicle-to-infrastructure (V2I) communication, and the cloud platform through vehicle-to-network (V2N) communication. Ultimately, all gathered perception data undergoes fusion processing at the host vehicle, leading to the derivation of final perception results.

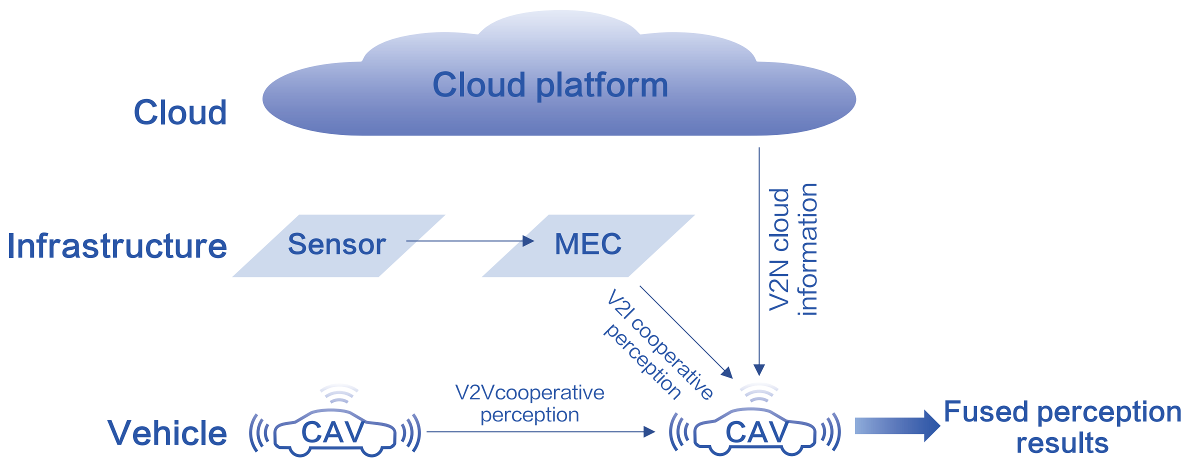


Figure 3.6 Schematic Diagram of Collaborative Perception

The utilization of vehicle-infrastructure cooperative perception has been shown to offer several significant advantages. These advantages can be primarily attributed to the following reasons:

Firstly, the deployment of infrastructure sensors provides numerous options for multi-directional and long-distance continuous deployment, enabling comprehensive and efficient monitoring of the traffic environment.

Secondly, the infrastructure and the cloud can acquire data through diverse methods such as mobile cellular access and wired access, overcoming the limitations of visual perception and cognition. For instance, this can be observed in the data collection of traffic lights. As a result, the investment required for computing power can be significantly reduced.

Thirdly, the infrastructure and the cloud enhance the semantic judgment and recognition of complex environments, traffic events, and traffic situations through long-term continuous detection. This leads to real-time and precise perception and recognition of various traffic events, such as "malfunctional vehicle", queuing, construction, and object scattering, among others.

The present study discusses the fusion perception strategy, which involves the integration of infrastructure multi-sensors. This process can be executed either in pre-fusion or post-fusion stages. The post-fusion approach entails a framework and process, as depicted in Figure 3.7, and comprises the following steps:

Firstly, a data container is used, which provides adaptive parameters, multiple message callbacks, and hot-swap interfaces. It converts all sensor messages, vehicle/infrastructure/cloud messages into a unified message format through built-in parameters and maps, and outputs them downstream.

Secondly, data association is performed. When information in the data container is sampled, all the information is sorted and matched based on trigger time. Chaotic position data is converted into a time-series state estimation. Before each match, the covariance is calculated according to the attributes of the data and their errors as the matching edge distance. After several matching iterations, the results are grouped and delivered to the state estimation module.

Thirdly, state estimation is performed, in which the state estimation module processes each group of information in a time-series-related manner and sends them to different filters established for stationary and moving objects.

Fourthly, state prediction is executed, in which the predicted state of the filter is processed by the map and the model. A short-term prediction message output is generated, which is sent back to the data association module to associate with the next sensor result and perform time series tracking.

Finally, the result output is generated, which includes the final fusion perception result information, such as position, speed, acceleration, heading angle, confidence, and other parameters.

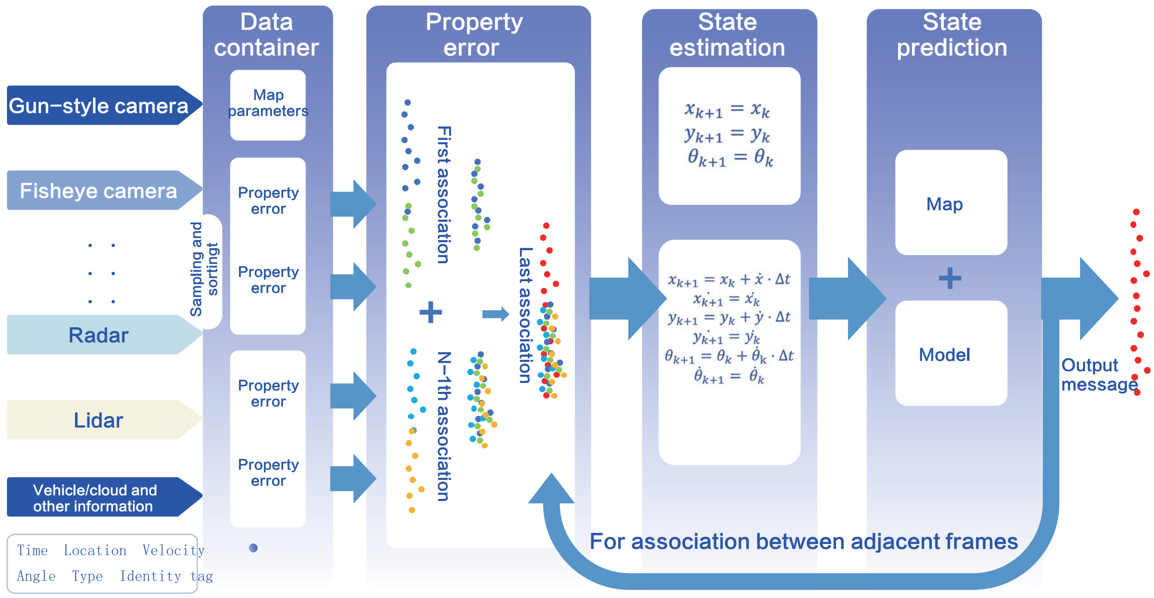


Figure 3.7 Framework of Infrastructure Multi-sensor Post-fusion Perception Positioning

Table 3.1 illustrates the potential use cases for cooperative perception between vehicles and infrastructure.

Scenario classification	Examples of specific scenarios
Collaborative perception and positioning of total traffic participants	Collaborative perception and positioning for dynamic and static blind area/occlusion
	Vehicle beyond-visual-range cooperative perception and positioning
	Collaborative perception and positioning of low-speed roadside vehicles
	Collaborative perception and positioning of low obstacles
	Collaborative perception and positioning in indoor, tunnel, mountain and other non-GNSS environments
Collaborative perception of traffic lights	Collaborative perception of traffic lights
Collaborative perception of traffic incidents	Such as overspeed, retrograde, congestion, illegal parking, queuing, object scattering, etc.
Traffic environment perception	Road traffic weather, road conditions, traffic infrastructure status and change information, etc.

Table 3.1 Use cases of Vehicle-infrastructure Collaborative Perception

(II) A Typical Cooperative Perception Scenario: Pedestrian-Intrusion Cooperative Perception

The current discourse centers on a common pedestrian intrusion scenario that often occurs in urban environments, and it explains the fundamental principle of vehicle-infrastructure cooperative perception. For additional examples of its application, readers are encouraged to consult Section 6.2.2.

Problem Description:

Pedestrian crossings and running red lights are typical occurrences in modern traffic environments. Autonomous vehicles frequently encounter difficulty predicting the path of low-speed pedestrians or responding swiftly to their sudden appearance, which can result in abrupt vehicle braking or a risk of collision.

Scenario Principle:

1) At the infrastructure level, continuous monitoring from multiple perspectives enables real-time identification, positioning, and trajectory prediction of pedestrians and non-motorized vehicles. This information generates state intention labels, including roadside waiting, construction, walking, crossing at a pedestrian crossing, crossing the road, among others.

2) The infrastructure transmits the total traffic targets identified at the intersection to the

vehicle in real-time via V2X, using sensor-sharing message (SSM) datasets[27] through radio. The vehicle promptly obtains the status and intention of the total traffic targets, making reasonable traffic decisions and controls, such as:

a) Crossing the street at a pedestrian crossing: The host vehicle stops actively (see Figure 3.8);
b) Pedestrians crossing the road: The host vehicle stops actively (see Figure 3.9);
c) Roadside construction personnel: The host vehicle decelerates and detours (see Figure 3.10);
d) Pedestrian waiting on the roadside: The host vehicle continues driving;
e) Pedestrian walking on the roadside: The host vehicle continues driving.

Application Benefits:
The vehicle receives perception information from the infrastructure, fuses it with the vehicle perception, and makes comprehensive decisions. As a result, it can safely navigate such scenarios, avoiding emergency brakes or accidents, and ensuring a better driving experience.

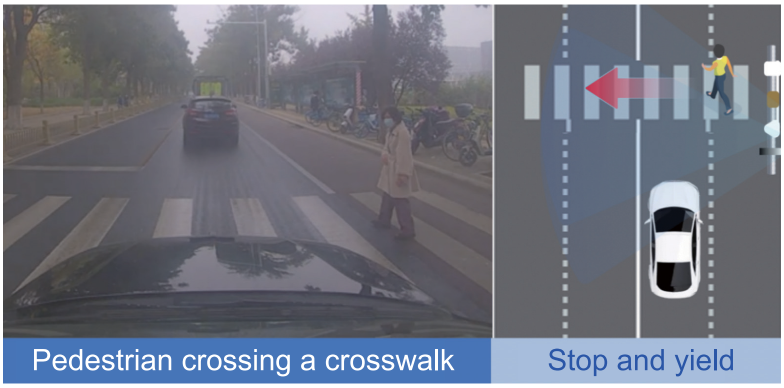


Figure 3.8 Parking Actively in case of Pedestrian Crossing Street

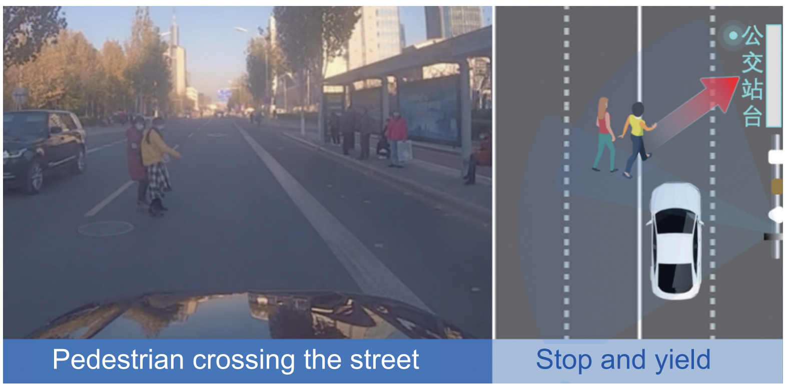


Figure 3.9 Parking Actively in case of Pedestrian Crossing Road

27. For the data frame, data elements, and data transmission requirements of the SSM dataset, please refer to the High-level Autonomous Driving Data Interaction Content Based on Vehicle-infrastructure Collaboration (YD/T 3978-2021)

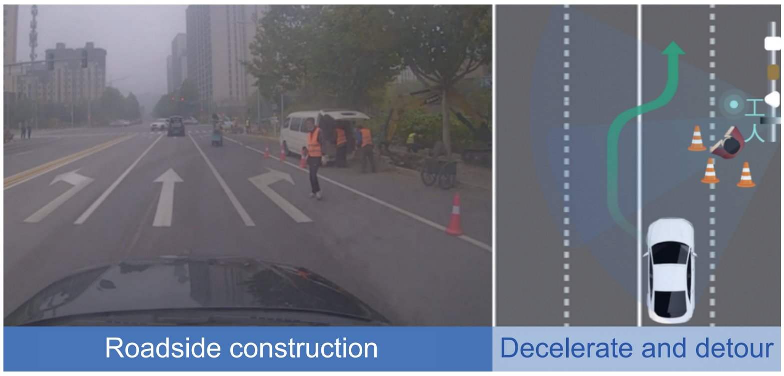


Figure 3.10 Decelerating and Detouring During Roadside Construction

(III) Example 2: Cooperative Perception and Positioning in Non-GNSS/Weak GNSS Environments

Problem Description:

Autonomous vehicles rely on GNSS+RTK for absolute positioning information and on IMU+wheel speed+steering wheel angle for relative positioning information. These are combined with HD maps and observation sensors for multi-sensor fusion positioning in open environments. However, in environments such as bridges, tunnels, underground areas, and mountainous regions, there is no effective absolute positioning information available, leading to inaccurate positioning results.

Scenario Principle:

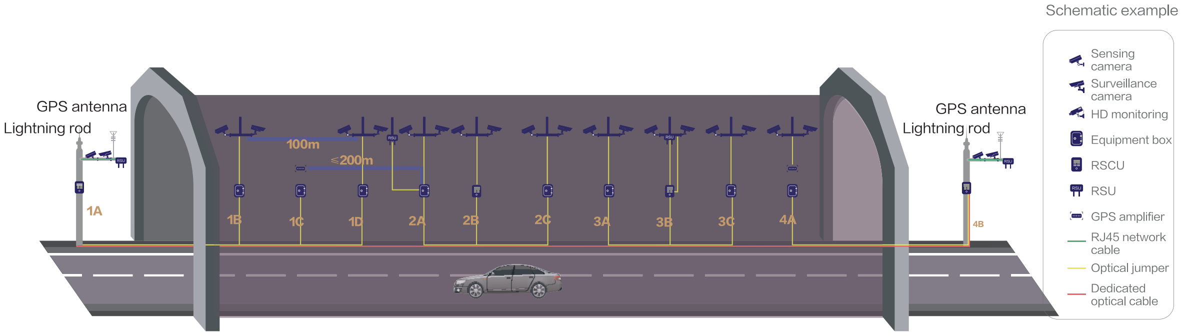
To address the challenges faced by autonomous vehicles in such environments, vehicle-infrastructure cooperation can be leveraged in several ways, including:

1) **Infrastructure multi-sensor fusion perception and positioning:** This approach involves matching infrastructure fusion perception and positioning information with the dynamic and static feature information of the vehicle to obtain real-time high-precision location information. The technology implementation principle is similar to that shown in Figure 3.7. Figure 3.11 demonstrates the application benefits of this solution in tunnels.

2) **Assistant positioning technical solution based on Ultra-wide Band (UWB) or Long-Term Evolution (LTE) PC5:** This approach involves deploying wireless positioning base stations/anchors and GNSS signal amplifiers at the infrastructure. Pre-position calibration enables the determination of the absolute location of each near-field wireless positioning base station/anchor, and the GNSS signal amplifier is used for the timing of the master clock of the vehicle and infrastructure in the absence of a strong GNSS signal. The vehicle is equipped with a wireless positioning receiver/tag to receive near-field wireless positioning signals with absolute time information, decode and calculate the

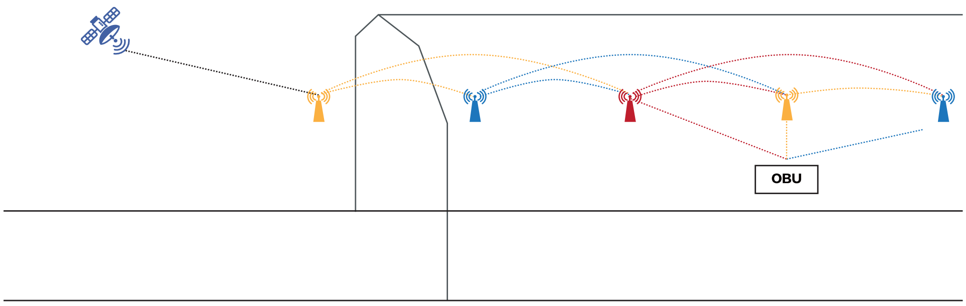
positioning information, and obtain high-accuracy positioning information. Figure 3.12 illustrates this approach.

3) **Positioning technical solution based on the fusion of infrastructure feature positioning markers and HD maps:** This approach involves leveraging infrastructure feature positioning markers and HD maps for positioning.



Note: This solution has been deployed and applied in projects such as Changsha Smart Expressway

Figure 3.11 Vehicle-infrastructure Collaborative Perception and Positioning Solution in Tunnels



Note: This solution is provided by CITIC Telecom International CPC Limited.

Figure 3.12 LTE PC5-based Vehicle-infrastructure Collaborative Positioning Solution in Tunnels

Application Benefits:

The application of various methods, including vehicle-infrastructure cooperative perception and positioning, ultra-wideband (UWB), LTE PC5, and feature positioning, has enabled autonomous vehicles to achieve high-accuracy positioning in challenging environments such as long tunnels or areas with weak GNSS signals. This achievement represents a significant step forward in the development of autonomous driving technology, as it has transformed positioning from an "Unknown" variable to a "Known" quantity.

3.2.1.2 Transforming "Unknown" to "Known" through real-time update of autonomous driving map

The autonomous driving map, also referred to as the "high-definition map" or "HD map," is a critical component of autonomous driving systems. Two main techniques are currently employed to map and update autonomous driving maps: professional mapping equipment and crowdsourced data collection using vehicle sensors. While the initial mapping process has successfully met the industrial requirements for high-level autonomous driving in terms of completeness and accuracy, the updating and maintenance of the map pose significant challenges.

The first method involves using professional mapping equipment to collect and produce the stock maps periodically. This technique typically involves manual mapping and is currently the primary method for map updating. However, this method is costly and requires specialized equipment, making it difficult to update large-scale maps in real-time.

The second method involves crowdsourced data collection using the real-time perception and positioning capabilities of smart cameras or advanced driver assistance systems installed in mass-produced vehicles.
The collected data is used to produce a map on the cloud, which is distinguished from the base map and used to update the autonomous driving map. While crowdsourced updates with massive vehicle terminals on open roads enable real-time updates of the high-definition (HD) map, they face significant challenges that limit their ability to support real-time HD map updates.

Firstly, there is a "bottleneck for vehicles passing for the first time," which refers to the invalidation of the map when vehicles pass for the first time after actual road changes. Secondly, mass-produced vehicles have limited computing power and positioning accuracy, which necessitates aggregating information collected multiple times within a period of time to generate high-confidence results before updating the map. Thirdly, uploading sensor data from vehicles to the cloud for mapping requires significant communication resources and incurs high data traffic costs. Additionally, transmitting sensor raw data with public networks poses major hidden dangers to national geographic information security.

There is a pressing need for high-level autonomous driving to update the autonomous driving map in real time due to the dynamically changing surrounding environment during driving, such as road structures, road ancillary facilities, and traffic operating conditions. Failure to update the map in real time may result in inconsistencies between the on-board map and the actual traffic environment, which can adversely affect the normal operation of autonomous driving.

Regardless of whether the map update data is obtained through professional HD mapping equipment or vehicle crowdsourced data, the problem of real-time updating of autonomous driving maps cannot be fully solved at present, with a high probability of encountering an "Unknown Scenario."

(I) Overall technical solution

In order to address the issues highlighted above, this paper proposes a real-time map update method for autonomous driving based on vehicle-infrastructure cooperation, specifically the local dynamic map update at the roadside bureau. This method supplements the commonly-used map update techniques in the industry. The principle of this approach is illustrated in Figure 3.13. The method involves high-frequency fixed-point observations conducted through intelligent facilities deployed at the roadside bureau to detect real-time changes in dynamic and static map elements and update the map within the coverage area. The updated map is then transmitted to the vehicle terminal and map vendor to facilitate factor-level fusion updates with the currently-used map version.

Compared to the conventional map update approaches, such as those involving professional mapping equipment and vehicle crowdsourced map update techniques, the local dynamic map update at the roadside bureau offers several advantages. These are summarized in Table 3.2, and are as follows:

Firstly, this method utilizes fixed-point observation data with high precision and reliability. The roadside bureau sensors that are installed and deployed support centimeter-level position accuracy detection, through accurate internal and external parameter calibration and multi-sensor fusion perception positioning. Additionally, for empirical map data that requires periodic observation, the roadside bureau is utilized as a fixed-point continuous observation unit, offering further advantages as illustrated in Figure 3.14.

Secondly, this approach exhibits strong real-time performance. With millisecond-level perception at the roadside bureau and minute-level map production, it supports minute-level map updates, thus providing advantages over traditional update methods.

Lastly, the local dynamic map update at the roadside bureau provides abundant identifiable information regarding dynamic and static map elements. The roadside bureau can identify important static and semi-static map element information, as well as semi-dynamic and dynamic map element information.

The process of achieving dynamic updates of autonomous driving maps through local dynamic map updates at roadside bureaus involves two key steps.

(1) Dynamic update of autonomous driving map

Typically, as shown in Figure 3.15, the autonomous driving map consists of two layers: the static layer and the dynamic layer. The static layer can be further subdivided into the static and semi-static layers, while the dynamic layer can be subdivided into the semi-dynamic and dynamic layers (additional layers can be included based on specific requirements).

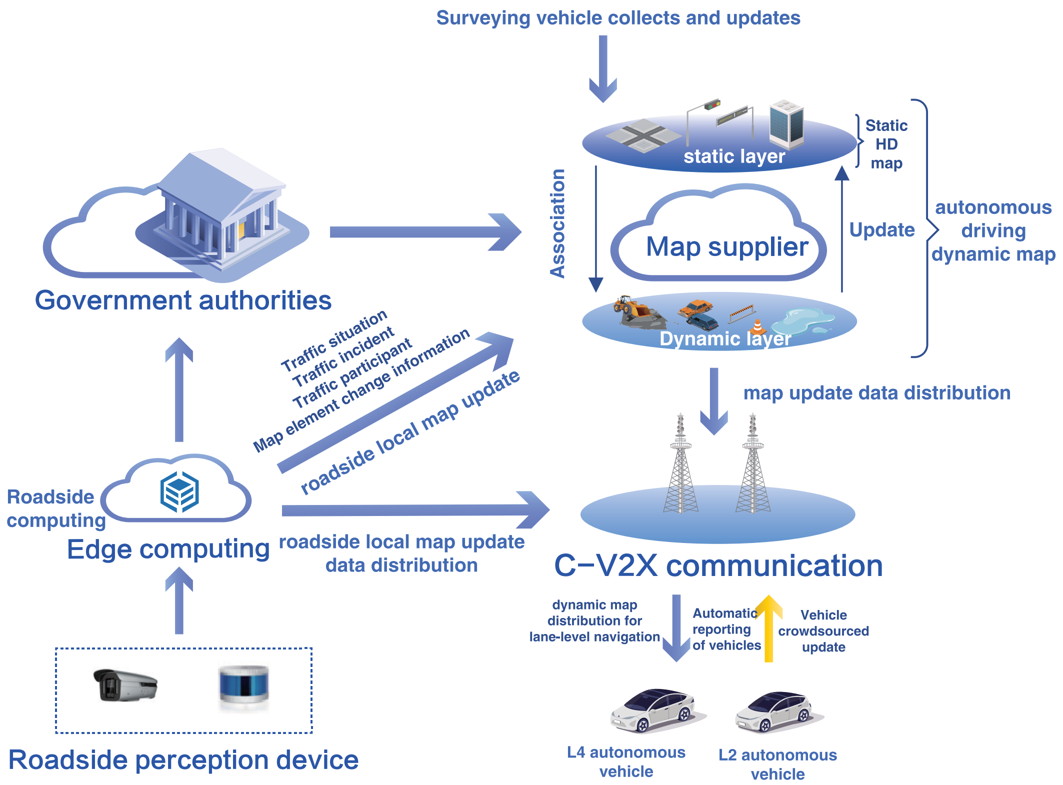


Figure 3.13 Overall Principle of Local Dynamic Map Update on the Roadside Bureau

Map update method	Relative accuracy	Real-time performance	Observation continuity	Coverage area	Cost estimate (10,000 yuan/km)
Mapping Vehicle Map Update	0.1m	-	Single-point observation	Full area coverage	Thousand yuan level
Vehicle crowdsourced map update	0.4m	Day-level	Breakpoint repeat observation	Most area covered	No need for new equipment investment
Partial Map Update on the Roadside Bureau	0.2m	Minute-level	Fixed-point continuous observation	Intersection coverage in area	No need for new equipment investment

Table 3.2 Comparison of Map Update Methods

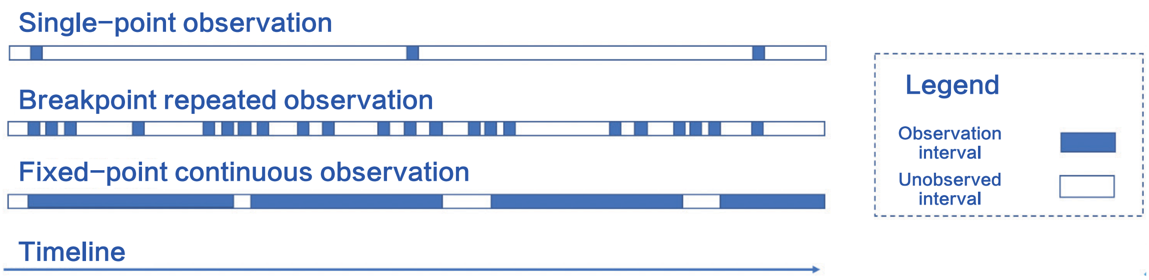


Figure 3.14 Comparison of Observation Continuity of Three Methods

As highlighted in Table 3.3, each layer has different requirements for real-time data and continuous observation periods. Map update methods based on roadside bureau perception are most advantageous for information that requires continuous observation periods and high-frequency periods, such as providing reasonable turn-left guide lines at intersections, identifying road blockage points with unknown reasons, and detecting low-speed driving intervals with unknown reasons.

Practical data analysis has revealed that delayed updates of the autonomous driving map can cause common "Unknown" scenario problems for L4 autonomous driving. As Table 3.4 demonstrates, over 80% of these problems occur at intersections, primarily due to two types of changes. Firstly, changes in physical map elements, such as modifications to traffic lights (including those for motor vehicle lanes, non-motorized vehicle lanes, and pedestrians), alterations to road signs and markings (including lane boundary lines, lane driving directions, stop lines, turn-left/turn-right waiting zones, and others), and modifications to traffic facilities (including fences/separation poles). Secondly, changes in empirical map elements, such as adjustments to lane connecting lines at intersections (including driving straight, turning left, and U-turn connecting lines), changes to road congestion points, and alterations to road driving behavior.

Therefore, adopting a local dynamic map update approach at roadside bureaus can effectively resolve most of the manual takeover problems that arise from map element changes in current autonomous driving scenarios.

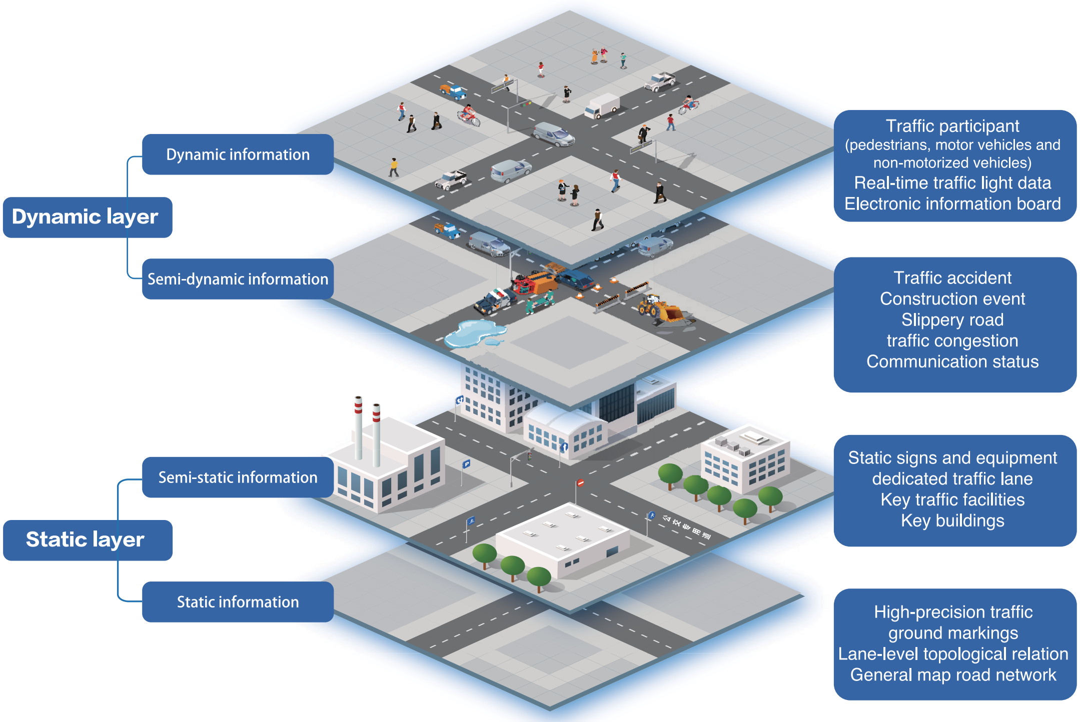


Figure 3.15 Layer Division for Dynamic Autonomous Driving Map

Layers	Layer classification standards	Acquisition method	Requirements for periodic observations
Static layer - static information	Fixed map elements such as road traffic equipment and facilities	Static extraction after one-time collection	None
Static layer- semi-static information	Variable map elements with fixed location but dynamic attributes	Static extraction after multiple collection	Long cycles, low frequency
Dynamic layer- semi-dynamic information	Empirical map elements including information with clear validity period, either one-time or periodic	Repeated collection and extraction	Continuous cycles, high frequency
(event and experience)	Map elements featuring instantaneous occurrence or short valid period	Real-time collection and rapid extraction	Short cycles, high frequency
Dynamic layer - dynamic information	Map elements featuring instantaneous occurrence or short valid period	Real-time collection and rapid extraction	Short cycles, high frequency

Table 3.3 Characteristics of Different Layers of Dynamic Autonomous Driving Map and Requirements for Periodic Observation

Map elements	Change method	Resulting problems	Potential consequences
Traffic light change in motorway	Traffic light misplacement	Failure to correctly recognize traffic light status, some traffic light positions cannot be recognized	Blocking (stop at green light) Violating traffic rules (run a red light)
	Traffic light removal	Failure to correctly identify traffic lights	Blocking (stop at green light) Violating traffic rules (run a red light)
	Traffic light added	Failure to correctly identify traffic lights	Blocking (stop at green light) Violating traffic rules (run a red light)
	Traffic light failure recovery	Failure to participate in decision-making after identifying traffic lights	Blocking (stop at green light) Violating traffic rules (run a red light)
	Traffic light failure	Failure to obtain correct traffic light state	Blocking (stop at intersection)
	Traffic light control direction change	Misrecognition of traffic light status	Violating traffic rules (run a red light)
	Lane number change	Failure to correctly recognize lane line	Collision risk Violating traffic rules (ride on bike lane lines)
	Lane repainting	Failure to correctly recognize lane line	Collision risk Violating traffic rules (cross multiple lanes)

Table 3.4 Some "Unknown" Scenario Problems Caused by Untimely Autonomous Driving Map Update

Sign change in lane line	Change in permissible flow direction	Misrecognition of lane direction	Collision risk (temporary lane change) Violating traffic rules (not following directional signs)
	Stop line shifting back	Misrecognition of stop line	Violating traffic rules (parking over the line)
	Change in waiting zone	Misidentification of waiting zone	Violating traffic rules (run a red light)
	Guardrail added	No viable driving zone	Collision risk
Change in dotted connecting lane at intersection	Entrance and exit connection relationship change	Perception error in predicting vehicle trajectory, failure to identify collision risk in a timely manner	Collision risk
		Merging with other vehicles in intersections	Collision risk
	Unreasonable U-turn virtual connection line	Error in turning or U-turn position, unable to complete the turn	Collision risk
	Unreasonable left-turn virtual lane drawing	Too close distance to traffic ancillary obstacles at intersections	Collision risk
Road driving behavior change	Road segment detour points added	Failure to effectively avoid unknown types of obstacles	Collision and blocking risk
	Detour road segment	Failure to effectively avoid unknown types of traffic events	Collision and blocking risk
	Low-speed driving section added	Failure to effectively recognize low-speed driving caused by unknown reasons on certain road segments	Collision and blocking risk
	Driving curve change	Failure to pass through turning areas	Collision and blocking risk

(2) Real-time map updates distribution

In order to effectively leverage the value of maps, the updated map data needs to be transmitted to the vehicle and applied to the vehicle's decision-making and planning. Currently, there exist diverse channels, contents, and forms of map delivery, and there is a demand for lossless and secure information flow across map vendors, car manufacturers, and module providers during the delivery process. Utilizing roadside infrastructure as a unified information dissemination channel, and sending local dynamic map data decoupled from map vendor map versions using the Map Reference Position Protocol (as detailed in Appendix A), is a critical means of ensuring the real-time and effectiveness of vehicle data. Moreover, this approach provides map vendors with an opportunity to leverage roadside information for version-level map updates.

(II) Example and Comparative Analysis of Typical Scenarios for Real-Time Map Updates.

To illustrate the common scenarios of traffic signal and lane line changes, we take these examples for discussion. Based on long-term observation and statistical analysis of multiple intelligent connected vehicle demonstration zones, it is apparent that autonomous vehicles have a high likelihood of encountering real-world road changes (such as traffic lights, lane lines, signs, etc.) during actual road driving. The frequency of encountering road changes per 10,000 kilometers, denoted as (MAD) , is approximately 6.38 times (including 5.5 times for traffic signal changes and 0.78 times for lane line changes). Such scenarios can directly impact the safe operation of autonomous vehicles and necessitate the prompt implementation of effective countermeasures. In the following sections, we will conduct a comparative analysis of two typical map update modes: crowdsourcing map updates and road-side local dynamic map updates.

(1) Vehicle Crowdsourced Map Update Mode

In this mode, the time required for the map to complete the update of real-world changes, denoted by D_{AD}, is typically on the order of day-level data accumulation (≥24h) due to the need to accumulate multiple trips and multi-lane data for complete reconstruction. Cloud-based map updates can only be issued after this accumulation is completed. Therefore, in the crowdsourced map update mode, the map update period is defined as D_{AD} =24h, assuming that the daily operating time of the autonomous vehicle, denoted by T_{AD}, is 10h.

The probability of encountering a map element change scenario in this mode can be obtained from two levels through long-term operational observations. Specifically, the probability of a single vehicle encountering the scenario per 10,000 km is denoted by M_{AD} =6.3 times/10,000 km, while the probability of a single vehicle encountering the scenario per day is denoted by N_{AD} =1.7 times/vehicle/day.

In this mode, the passing rate of a vehicle encountering a map element change scenario only depends on the capacity of a single vehicle. The passing rate for the map element change scenario is defined as $P_{AD|change}$, and should be determined based on the actual capacity of the vehicle and a large number of measured results.

(2) Local Dynamic Map Update Mode at Roadside

In this mode, the roadside perception is utilized to facilitate the rapid update of road traffic elements on the cloud-based map, which can be subsequently updated on the vehicle side. The update time, denoted by D_(VICAD), is defined as the total time required to complete the update process, including the time for cloud-based map rebuilding and vehicle-side updating. Conservatively, D_{VICAD} is estimated to be 5 minutes.

$$D_{VICAD} = 5\ \text{min}$$

Assuming that the recall rate, denoted by R_{VICAD}, of scene updates achieved through vehicle- Infrastructure coordination perception is 99.9%, the encounter rates of autonomous vehicles encountering scene changes under this map update mode are denoted by M_{VICAD} and N_{VICAD}. However, the values of M_{VICAD} and N_{VICAD} cannot be calculated based on the limited information provided:

$$\text{let } r = \frac{\min\left(T_{vehicle}, D_{single\ vehicle}, D_{edge}\right)}{\min\left(T_{vehicle}, D_{single\ vehicle}\right)}$$

$$M_{VICAD} = M_{AD} \times (r + (1-r) \times (1 - R_{VICAD})) = 0.0587 \text{ times/10,000 km}$$
$$N_{VICAD} = N_{AD} \times (r + (1-r) \times (1 - R_{VICAD})) = 0.00159 \text{ times/vehicle/day}$$

In terms of scenario success rate, if there is a real-time change in map elements during the operation time, and the map element change scene occurs at time t_1, and a vehicle passes through the point at time t_2, then within the time window of t_1 to min (T_{AD}, t_1 + D), the vehicle is affected by the scene environment with a success rate of $P_{AD|change}$. Before the time window, the vehicle passes with a success rate of $P_{AD|change}$ = 1. After the time window, if the vehicle completes the update, the success rate will be restored to $P_{AD|change}$. Therefore:

$$p(t_1, t_2, D, R) = \begin{cases} P_{AD|\text{unchanged}}, & t_2 < t_1 \\ P_{AD|\text{changed}}, & t_1 \le t_2 \le \min(T_{\text{vehicle}}, t_1 + D) \\ P_{\text{Single-vehicle } AD|\text{changed}}(1 - R) + P_{AD|\text{unchanged}} R, & t_2 > t_1 + D \end{cases}$$

The scenario passing rate after the introduction of local dynamic map update is:

$$P_{VICAD|\text{changed}} = \frac{\int_0^{T_{AD}} \int_{T_{AD}-D_{AD}}^{T_{AD}} p(t_1, t_2, min(D_{AD}, D_{VICAD}), R_{VICAD}) dt_1 dt_2}{\int_0^{T_{AD}} \int_{T_{AD}-D_{AD}}^{T_{AD}} p(t_1, t_2, D_{AD}, 1) dt_1 dt_2}$$

$$\text{because } D_{\text{edge}} \ll T_{\text{vehicle}} < D_{\text{single vehicle}}, \text{ available:}$$

$$P_{VICAD|\text{changed}} \approx (1 - \left(1 - P_{AD|\text{changed}}\right)(1 - R_{VICAD}))(1 - \frac{D_{VICAD}}{D_{AD}}) + P_{AD|\text{ changed}} \times \frac{D_{VICAD}}{D_{AD}}$$

Based on the measurement and operation data of a large number of autonomous vehicles, the following can be further calculated:

Assuming a map feature change scenario under AD mode with a success rate of $P_{AD|change}$ = 90%, and a recall rate of R_{VICAD} = 99% under the road-side partial dynamic map update mode, the probability of encountering a change scenario under VICAD mode can be obtained as $P_{AD|change}$ ≈ 99.86%.

Assuming a map feature change scenario under AD mode with a success rate of $P_{AD|change}$

= 99.8%, and a recall rate of R_{VICAD} = 99.9% under the road-side partial dynamic map update mode, the probability of encountering a change scenario under VICAD mode can be obtained as $P_{AD|change}$≈ 99.999%.

(3) Benefit evaluation analysis

In summary, the road-side partial map update mode has significant benefits, as shown in Table 3.5, which are as follows:

Regarding map update time, D_{VICAD} is less than or equal to 5 minutes, and the map update time is significantly shortened.

The probability of encountering a map feature change scenario is significantly reduced. With R_{VICAD} = 99.9%, the scenario encounter rate can be reduced from 6.38 times/10,000 kilometers to 0.0587 times/10,000 kilometers.

The success rate of scenario passing is significantly improved.
Under the condition of $P_{AD|change}$ = 99.8% and R_{VICAD} = 99.9%, $P_{AD|change}$ can even reach the ideal value of 99.999%, and the failure rate of scenarios can be reduced from 1.26 times/million kilometers to 0.0063 times/million kilometers.

Map update method	Map update time/D	Scenario encounter frequency/M	Scenario success rate/P	
			Condition 1: R_{VICAD} =99%	Condition 2: R_{VICAD} =99.9%
Vehicle crowdsourced map update	≥24h	6.38 times/10,000 km	$P_{AD|Change}$ = 90%	$P_{AD|Change}$ = 99.8%
Local dynamic map update at roadside bureau	≤5 min	0.0587 times/10,000 km (in case of R_{VICAD} = 99.9%)	$P_{VICAD|Change}$ ≈ 99.86%	$P_{VICAD|Change}$ ≈ 99.999%

Table 3.5 VICAD Benefit Analysis in Map Element Change Scenario

3.2.2 Transforming "Unsafe" scenarios into "Safe" scenarios

VICAD is a technology that not only enables the transformation of "unknown" autonomous driving scenarios into "known" ones, but also integrates advanced technologies such as Vehicle-Infrastructure cooperative perception, decision-making and control, to effectively convert "unsafe" scenarios into "safe" ones, thereby significantly enhancing the safety of autonomous driving systems. As illustrated in Table 3.6, "unsafe" autonomous driving scenarios can be broadly classified into three categories.

The first category pertains to safety in interactive game scenarios. In these scenarios, when vehicles conflict with each other, roadside bureaus and the cloud function as "arbitrators" to determine the priority of road use rights. They carry out cooperative decision-making and planning to prevent dangerous scenarios caused by conflicts. When vehicles conflict with people, protection strategies for vulnerable traffic participants must be adopted. This involves issuing avoidance, slowing-down, or stop instructions to vehicles to protect pedestrians' safety.

The second category pertains to safety in extreme or special scenarios. While the probability of autonomous vehicle malfunctions or extreme scenarios is relatively low, the consequences of such events can be severe, resulting in multiple vehicle collisions and hazards. The VICAD technology, with its vehicle-infrastructure cooperative decision-making, planning, and control functions, can effectively prevent such accidents.

The third category pertains to environmental safety. The safety of autonomous vehicles is closely linked to the complexity of the vehicle operating environment. Simplifying the environment enhances safety, while increasing complexity poses safety challenges for autonomous vehicles. VICAD offers the ability to manage environmental complexity, such as non-motorized vehicle/pedestrian safety, and traffic accident prevention. This helps ensure the safe and orderly operation of vehicles and all traffic participants.

Scenario classification	Typical scenario	Methods of transforming "Unsafe" scenarios into "Safe" scenarios
Safety in interactive game scenario	• Merge and exit ramps • Lane changing and overtaking • Crossing at intersections without traffic signals • Priority passage for vehicles • Station entrances and exits, etc.	"Vehicle control": On the basis of vehicle-infrastructure cooperative perception, and through VICAD, the real-time control of CAV is realized, to improve the safety of autonomous driving.
Safety in extreme or special scenario	• Vehicle breakdown • Extreme congestion,road congestion/blocking • Vehicle-trapped scenario	
Environmental safety	• Rain, snow and fog • Non-motorized vehicle and pedestrian safety management • Road construction and traffic accident safety • Low littering • Road flooding and subsidence • Tunnel accidents, fires, etc.	"Environment control": By controlling the traffic infrastructure and inducing and controlling traffic operations, CAVs are indirectly controlled, thus improving the safety of autonomous driving.

Table 3.6 Examples of Transforming "Unsafe" Scenarios into "Safe" Scenarios

Among them, safety in interactive game scenarios and in extreme or specialized scenarios can be transformed from an "Unsafe" to a "Safe" status through "vehicle control." This refers to direct involvement in the decision-making and control process of CAVs using VICAD, thereby influencing the driving behavior of the vehicle, as illustrated in Figure 3.16.

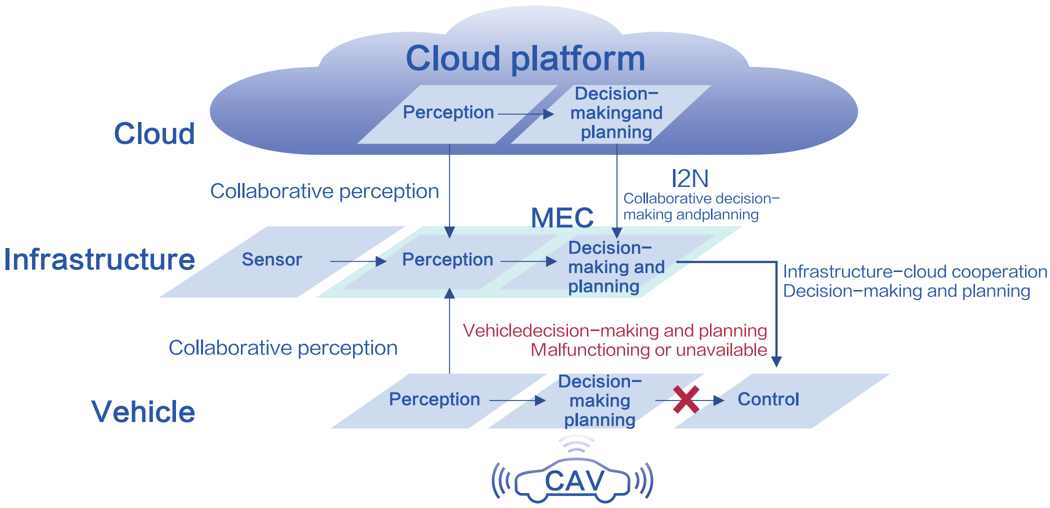


Figure 3.16 Transforming "Unsafe" to "Safe" through Direct Vehicle Control using VICAD

The improvement of environmental safety can be achieved by transitioning from an "Unsafe" to a "Safe" status through the implementation of "environment control" measures. This approach involves the direct manipulation of road infrastructure and equipment using VICAD, as well as indirect participation in the decision planning and control processes of CAVs. By leveraging these techniques, the driving behavior of vehicles can be effectively influenced, as illustrated in Figure 3.17.

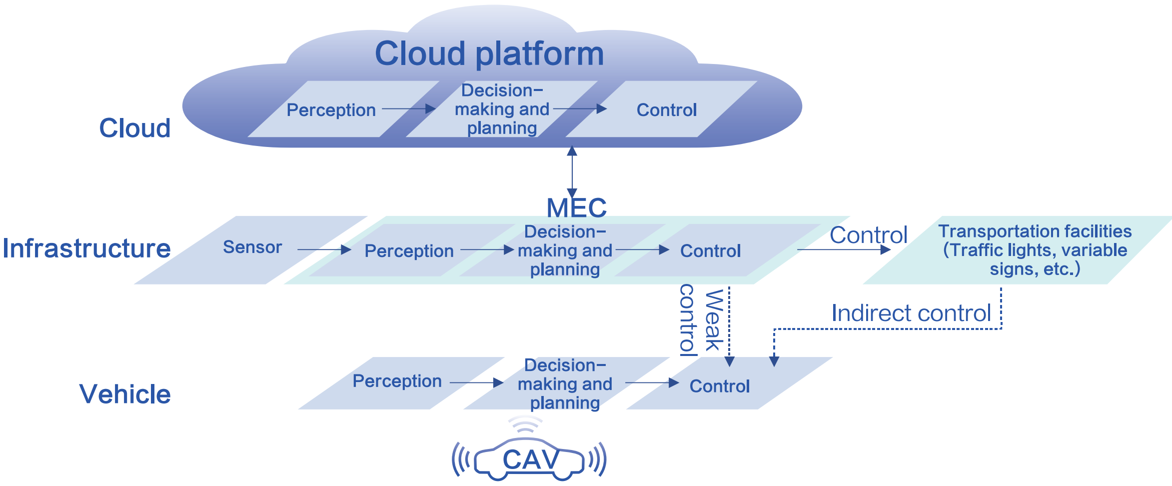


Figure 3.17 Transforming "Unsafe" to "Safe" Through Environment Control of VICAD

3.2.2.1 Transforming from "Unsafe" to "Safe" through "vehicle control"

(I) Overall technical principle

As depicted in Figure 3.18, an autonomous driving system typically comprises several modules such as perception, prediction, and positioning, as well as path planning (routing), behavior decision-making (decision), motion planning (planning), and control (control).

Additionally, by virtue of cooperative perception, the Vehicle-Infrastructure Cooperative Autonomous Driving (VICAD) system plays a critical role in decision-making and control, facilitating deep cooperation across three levels: dynamic path planning, collaborative decision planning, and collaborative control.

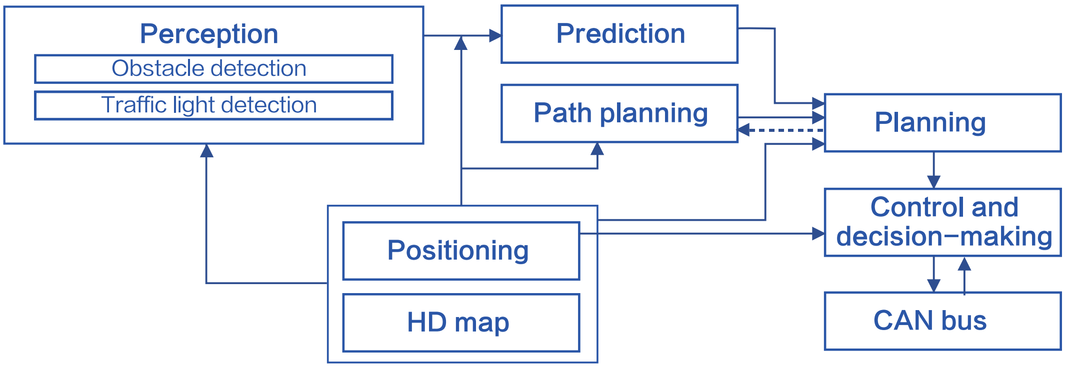


Figure 3.18 Overall Flow of Autonomous Driving Perception, Decision Planning and Control

(1) Dynamic path planning

Dynamic path planning involves the continuous optimization and adjustment of driving routes by integrating various sources of information during the driving process of autonomous vehicles, including standard road network maps, HD maps, lane-level traffic situations, and lane-level traffic incidents. The objective of this module is to achieve real-time optimization of routes while ensuring safety and maximizing the efficiency of traffic travel. As shown in Figure 3.19, the recommended route from the vehicle's location to the destination is displayed on the map, allowing the autonomous vehicle to choose the optimal path according to actual needs, such as the shortest time and the simplest traffic scenario.

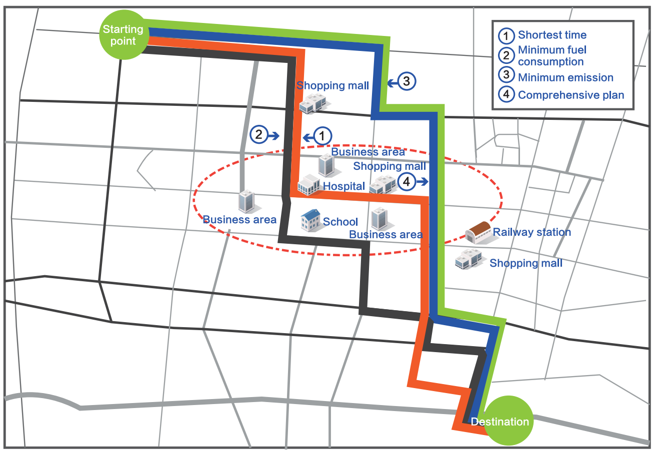


Figure 3.19 Technical Principle of Dynamic Path Planning in Autonomous Driving

Dynamic path planning has clear advantages in various application scenarios, including avoiding congested intersections, bypassing road-occupying construction, and dynamic formation of vehicles. Other related application scenarios are as shown in Table 3.7.

Application classification	Specific application	Benefits from L4 autonomous driving	Advantages over single-vehicle path planning
Safety application	Dynamic path planning for traffic incidents	Avoid falling into complex extreme scenarios	Deal with complex scenarios calmly
	Guarantee traffic and positioning stability	Guarantee the acquisition of lane-level positioning + real-time information	More secure positioning and communication
	Detour from bad road environment	Ensure vehicle control safety	Safer road driving environment
	Low-visibility traffic	24/7 driving	More flexible driving conditions
Efficiency application	Green light optimal speed	Reduce waiting time at intersections	Shorter waiting time
	Avoid congestion	Reduce running time	Higher average speed
	Right-of-way reservation and management	Improve operational efficiency	More orderly roads
	Formation driving	Reduce driving complexity	Higher driving speed

Table 3.7 Typical Applications of Dynamic Path Planning in L4 Autonomous Driving

(2) Collaborative decision-making and planning

Collaborative decision planning, comprising cooperative decision-making and cooperative motion planning, can be viewed as the key to the success of VICAD. In vehicle-infrastructure cooperative decision-making, as illustrated in Figure 3.20, the analysis and judgment of the driving scenario and the trajectory prediction of key obstacles are completed based on the input information of vehicle-infrastructure cooperative perception, high-accuracy positioning, and global path planning. Subsequently, the decision theory, such as the markovian decision process, is employed to make optimal vehicle decision-making judgments in the decision space set, taking into account traffic rules, historical decision information, driving experience, and other prior knowledge.

The overall framework of vehicle-infrastructure cooperative motion planning, as shown in Figure 3.21, evaluates the optimal trajectory planning results for vehicle control and execution based on trajectory evaluation systems, such as driving comfort evaluation, accessibility evaluation, safety evaluation, and traffic efficiency evaluation, combined with optimal decision-making result data.

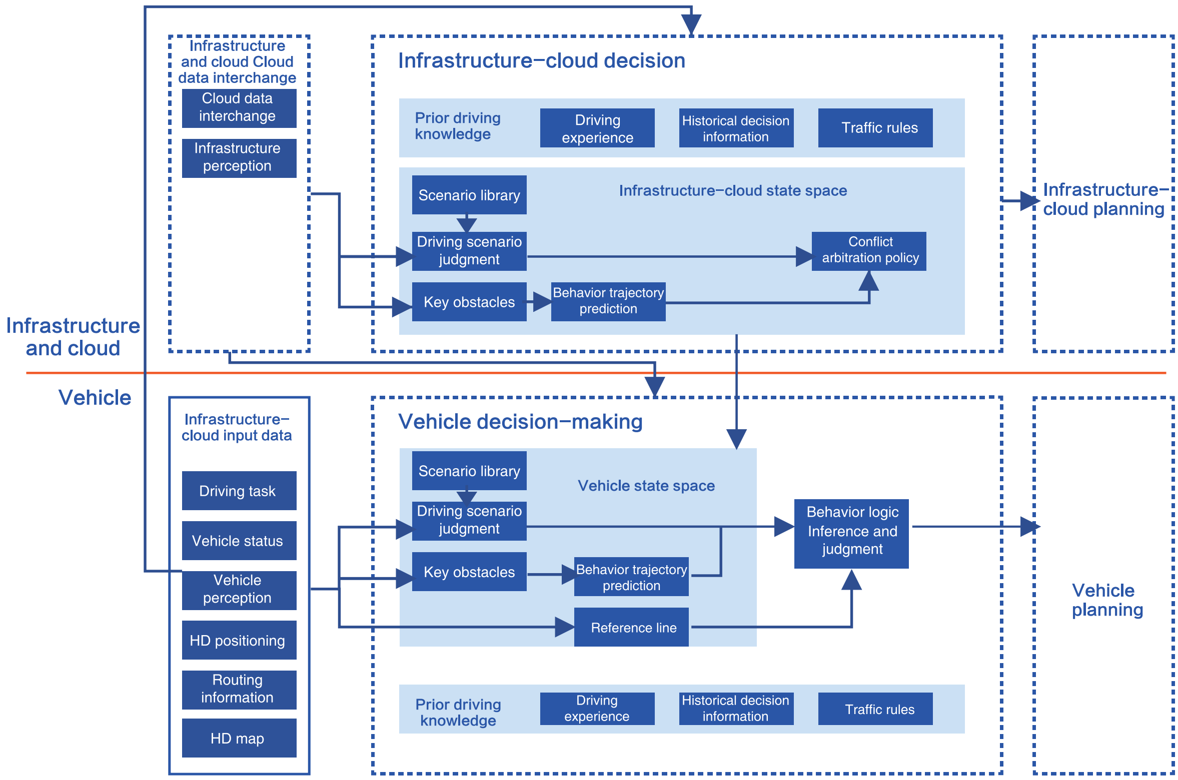


Figure 3.20 vehicle-infrastructure Collaborative Decision-making Process

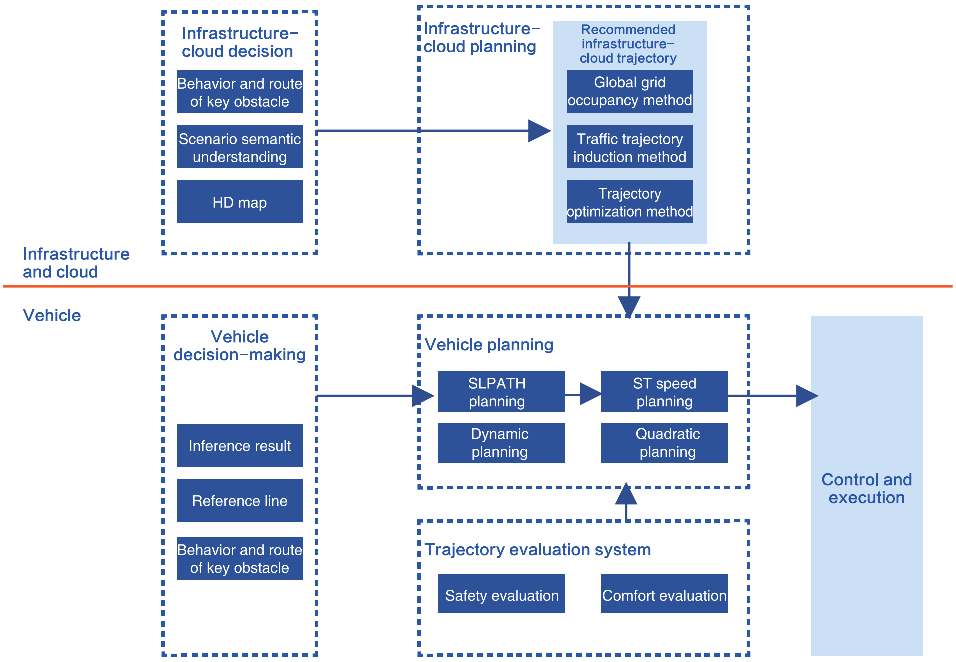


Figure 3.21 Vehicle-infrastructure Collaborative Motion Planning Process

<table>
<tr><th colspan="2">Scenario classification</th><th rowspan="2">Scenario name</th><th rowspan="2">Vehicle-infrastructure cooperative decision-making and planning strategy</th></tr>
<tr><th>Primary classification</th><th>Secondary classification</th></tr>
<tr><td rowspan="9">Interactive conflict scenarios</td><td rowspan="4">Conflict with motor vehicles</td><td>Changing lanes and overtaking</td><td rowspan="4">1. The vehicle-infrastructure collaborative perception provides real-time perception and positioning for all traffic participants.
2. If the path planning can solve it, perform global path planning in advance to avoid conflicts.
3. When path planning cannot solve the issue:
1) Decision-making: Develop a driving strategy for the vehicle (a. follow; b. overtake; c. detour; d. accelerate; e. decelerate, etc.);
2) Motion planning: (optional) Recommend the speed of the main vehicle and suggest local trajectory planning.</td></tr>
<tr><td>Ramp diversion and merging</td></tr>
<tr><td>Left- and right-turn conflict</td></tr>
<tr><td>U-turn conflict</td></tr>
<tr><td rowspan="5">Conflict with pedestrians and single vehicles</td><td>Running a red light</td><td rowspan="5">1. Vehicle-to-infrastructure cooperative perception provides real-time perception and positioning for all traffic participants.
2. Decision-making: formulate main vehicle passing strategies (a. slow down and avoid; b. detour and pass; c. pass normally).
3. Motion planning: (optional) recommend main vehicle passing speed and trajectory suggestions.</td></tr>
<tr><td>Crossing the road</td></tr>
<tr><td>Occupying the road</td></tr>
<tr><td>Retrograde</td></tr>
<tr><td>Overspeed, etc.</td></tr>
<tr><td>Road congestion scenario</td><td>Traffic incident</td><td>Queuing and congestion</td><td>1. Vehicle-Infrastructure Cooperative Perception provides real-time perception and positioning for all traffic participants.
2. If the Routing path planning can solve the problem, perform global path planning in advance to avoid blockages.
3. If Routing path planning cannot solve the problem:
1) Behavior Decision: develop a driving strategy for the vehicle (a. follow; b. overtake; c. detour; d. accelerate; e. decelerate, etc.);
2) Motion Planning: recommend local trajectory planning suggestions and driving speeds.
4. If Routing path planning, Behavior Decision, and Motion Planning cannot solve the problem, it is necessary to solve it through vehicle-infrastructure cooperative control.</td></tr>
</table>

Table 3.8 Challenge Scenarios and Solutions for Autonomous Driving Decision Planning

Through the cooperation of vehicle-infrastructure cooperative decision-making and motion planning, VICAD can effectively address two types of challenging scenarios: autonomous driving interaction conflicts and road congestion. For instance, in interactive conflict scenarios, VICAD can provide cooperative decision-making proposals and passing strategies in terms of the driving direction, driving speed, and driving order of conflicting vehicles based on the state perception and intention prediction of global traffic participants. In road congestion scenarios, VICAD can develop reasonable detour or passing strategies based on the semantic understanding of congestion scenarios and the perception results of traffic situations. Details of these two scenarios are presented in Table 3.8.

(3) Collaborative control

VICAD can further participate in the control process of autonomous driving through indirect or direct control, depending on the control methods. Indirect control involves controlling traffic infrastructure (such as traffic lights) or traffic flow, while direct control refers to real-time control of the vehicle in a specific environment or scenario. An example of direct control is illustrated in Figure 3.22, where the vehicle-infrastructure cooperative control can assist the L4 autonomous vehicle in dealing with complex traffic environments, driving out of the geo-fence, or facing complex cognitive interaction scenarios or extreme scenarios. The cloud-based smart cockpit periodically receives information from the vehicle and infrastructure, and control instructions are sent to the vehicle chassis through the steering wheel and pedals of the cloud smart cockpit to realize remote control driving, leveraging two complementary communication links to issue control instructions, namely 4G/5G and infrastructure RSU.

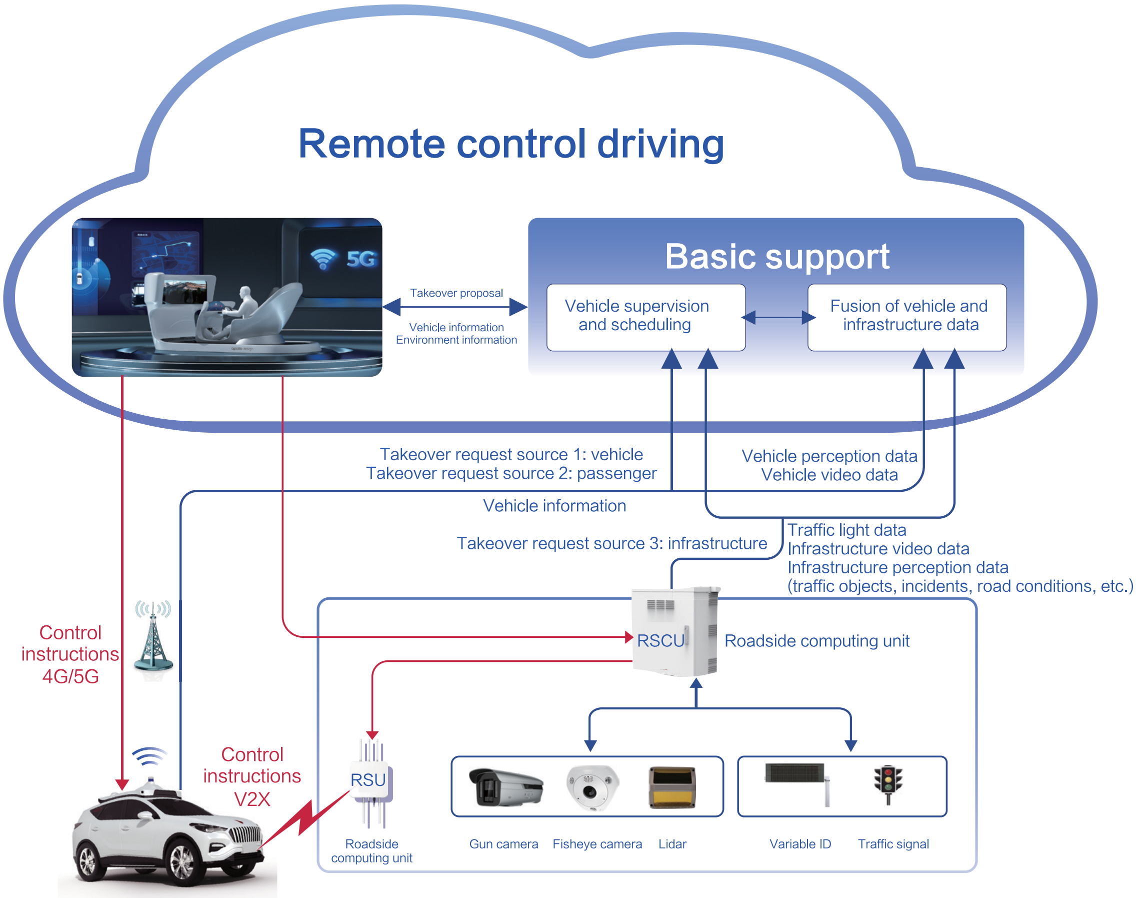


Figure 3.22 Principle and Overall Flow of Vehicle-infrastructure Collaborative Control

(II) Examples of typical scenarios of cooperative decision control

VICAD system provides an effective solution to improve the safety of autonomous driving in construction scenarios.

Problem description:

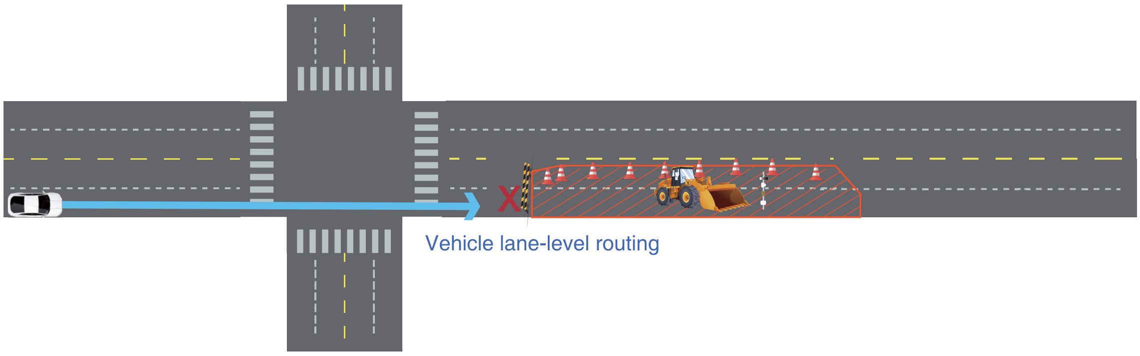
Road construction is a challenging scenario for autonomous driving. It poses significant challenges in terms of dealing with traffic incidents, especially in complex road construction scenarios such as construction in intersections, and construction occupying all lanes in the direction of travel. Current methods, such as vehicle-infrastructure cooperative perception or dynamic map update, are insufficient to cope with these scenarios, which can lead to vehicle stagnation or takeover, and potentially endanger the safety of autonomous driving.

Scenario principle:

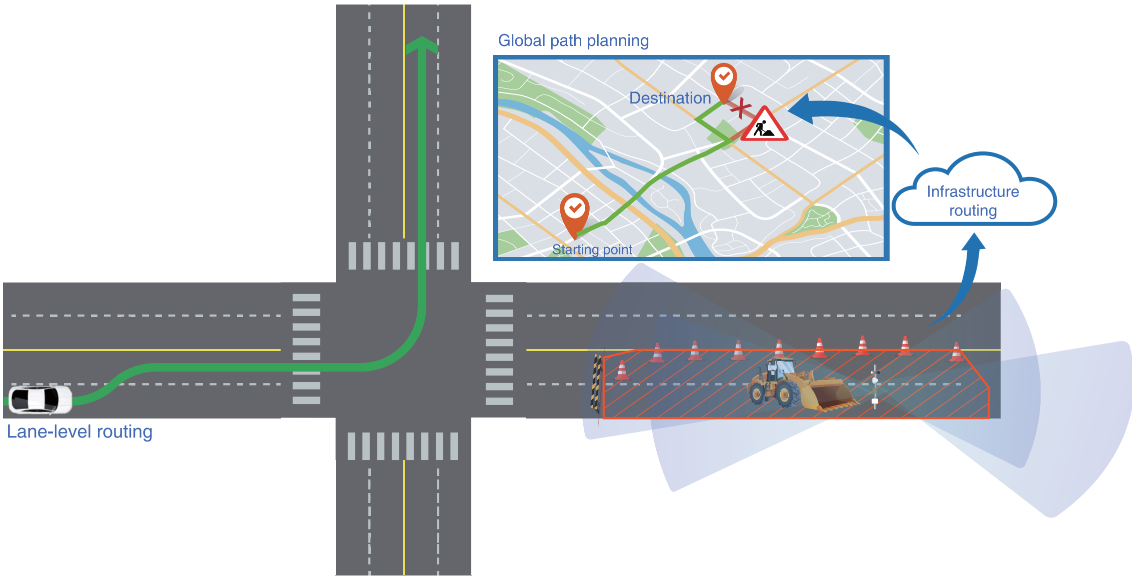
To address the challenges posed by construction scenarios, VICAD provides three solutions: dynamic path planning, cooperative decision planning, and cooperative control.

(1) Advance routing with dynamic path planning:

As shown in Figure 3.23. VICAD's dynamic path planning solution enables the infrastructure to identify construction information and send it to the map platform, including incident type, time and location, influence scope, influence time, etc. Through vehicle-infrastructure cooperative path planning, the possibility of vehicles passing through the construction section can be evaluated. If the possibility is low, the path can be re-planned to avoid the construction section in advance. The process includes global path planning, construction detection, cloud synchronization, and topological relation update, followed by global path re-planning to avoid the road section of the construction area in advance.



a) Single-vehicle intelligent autonomous driving construction scenario: certain probability of emergency stops or taking over

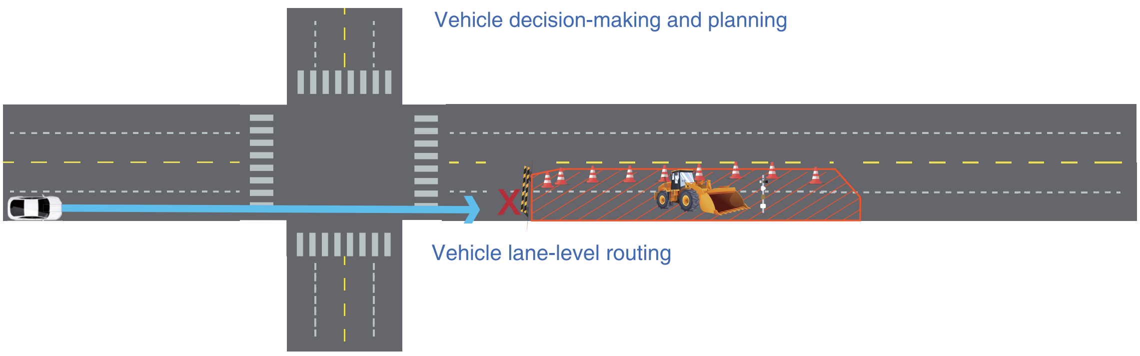


b) VICAD-based: driving path changed in advance with dynamic path planning

Figure 3.23 Dynamic Path Planning for Construction Scenario

(2) Detour based on cooperative decision planning

VICAD's cooperative decision planning solution provides an alternative approach by changing the vehicle's travel path in advance. Through vehicle-infrastructure cooperative perception, road blockage areas, causes, accessibility, etc. are identified, real-time and continuous observation is carried out for two-way traffic flow to obtain traffic flow trajectories around the blockage area. Based on the judgment of the road traffic situation, it is determined whether the driving direction of the innermost lane of the opposite side road can be temporarily changed to serve as the lane of the blocked road. The infrastructure updates the road topology data in the local area, and the vehicle re-plans the local route to use the opposite road to pass through the road section of the construction area, as shown in Figure 3.24.



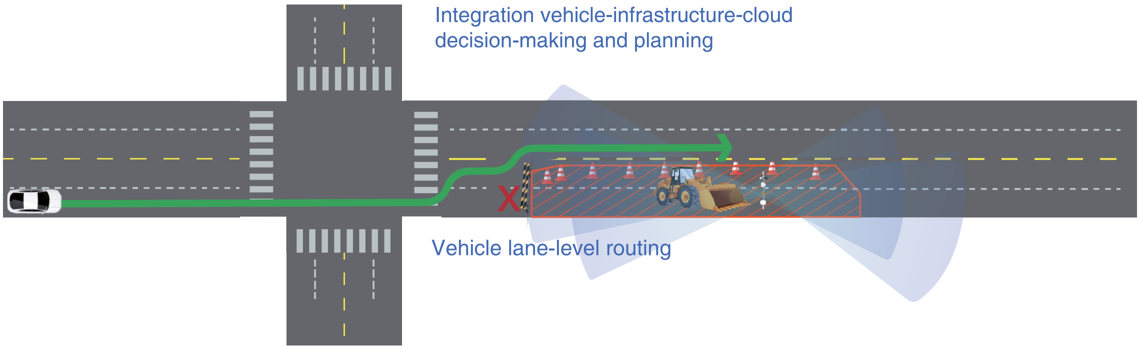


Figure 3.24 Vehicle-infrastructure Collaborative Decision Planning for Construction Scenarios

(3) Detour based on vehicle-infrastructure cooperative control

If the above two methods fail to cope with the construction scenario, the CAV may initiate a takeover request, allowing the cloud to take over the vehicle and help it pass through the construction-blocked road section through remote control driving. The process includes the initiation of a takeover request by the vehicle, the reception of the request by the cloud remote control driver, the synchronous upload of all kinds of real-time data at the vehicle/infrastructure to the cloud, and the decision-making and control by the remote-control driver to steer, accelerate, brake, etc. in the cockpit, followed by the execution of the remote driving control instructions by the vehicle to get out of the trouble, as shown in Figure 3.25.

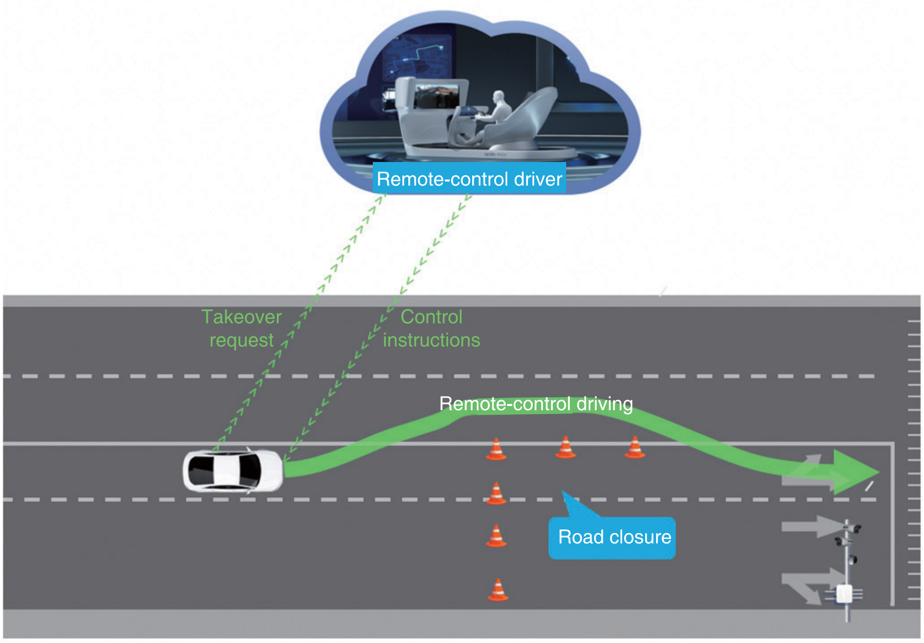


Figure 3.25 Vehicle Initiating Active Takeover Request in case of Cross-road Blocking

(III) Comparison of Vehicle-Infrastructure Cooperative Decision-making and Planning with Single-Vehicle Intelligence Application

In this section, we quantitatively compare and analyze two decision planning modes for autonomous vehicles in the context of infrastructure construction scenarios: (1) AD-based single-vehicle decision-making and planning mode, and (2) VICAD-based decision-making and planning mode.

(1) AD-based single-vehicle decision-making and planning

In the AD-based mode, the autonomous vehicle encounters an average of 4.5 construction incidents (M_{AD}) per 10,000 km. The duration for scenario recall in AD mode is defined as D_{AD} = 24 h, and the daily operating hours of autonomous vehicles are defined as T_{AD} = 10 h. The success rate of single-vehicle intelligent autonomous driving in this scenario is defined as P_{AD}, which can be obtained from measured data.

(2) VICAD-based vehicle-infrastructure decision-making and planning

Through infrastructure-cloud cooperative perception, decision-making and planning, construction events can be accurately identified and planned within a short time, and sent to the vehicle. For conservative estimation, the time for the entire link is set at 3 min, then:

$$D_{VICAD} = 3 \text{ min}$$

The scenario recall rate (R_{VICAD}) for construction events can reach up to 99.9% within the 3-minute time period. The encounter frequency of construction incidents in the vehicle-infrastructure cooperative decision-making and planning mode is reduced by routing, decision-making, and planning. The encounter frequency of construction incidents in this mode is:

$$M_{VICAD} = M_{AD} \times \left(\frac{\min\left(T_{vehicle}, D_{single\ vehicle}, D_{edge}\right)}{\min\left(T_{vehicle}, D_{single\ vehicle}\right)} + \left(1 - \frac{\min(T_{AD}, D_{AD}, D_{VICAD})}{\min(T_{AD}, D_{AD})}\right) \times (1 - R_{VICAD})\right)$$
$$= 0.0270 \text{ times/10,000 kmvehicle}$$

The passing rate of the scenario in this mode follows a lognormal distribution: $l \sim L, \ln(l) \sim N(\ln(2), \ln(6))h$. During operation time, if a scenario occurs at time t_1, the duration distribution is $\sim L$, and a vehicle passes by this point at time t_2, then within the time window from t_1 to $\min(T_{AD}, t\_1+l, t\_1+D), l \sim L$, the vehicle will be affected by the scenario environment, and its passing rate will be $P_{unrecognized\ |\ construction}$. If the construction continues and the recall is completed after the time window, the passing rate will be $P_{recognized\ |\ construction}$ = 1, and the passing rate of vehicles in the rest of the time will be $P_{no\text{-}construction}$ = 1.

$$p(t_1,t_2,D,R)=\begin{cases} P_{\text{no-construction}}, & t_2<t_1 \\ P_{\text{unrecognized/construction}}, & t_1\le t_2<\min(T_{\text{vehicle}},t_1+D), l\sim L \\ P_{\text{unrecognized/construction}}(1-R)+P_{\text{recognized/construction}}R, & \min\left(T_{\text{vehicle}},t_1+D\right)\le t_2<\min(T_{\text{vehicle}},l), l\sim L \\ P_{\text{recognized/construction}}, & t_2>l, l\sim L \end{cases}$$

The scenario passing rate after the introduction of vehicle-infrastructure cooperative decision-making and planning can be calculated as follows:

$$P_{\text{VICAD|construction}}=\frac{\int_0^{T_{AD}}\int_{-\infty}^{T_{AD}} p(t_1,t_2,\min(D_{AD},D_{VICAD},R_{VICAD})dt_1dt_2}{\int_0^{T_{\text{vehicle}}}\int_{-\infty}^{T_{\text{vehicle}}} p(t_1,t_2,D_{AD},1)dt_1dt_2}$$

because $D_{edge} \ll T < D_{\text{single vehicle}}$, available:

$$P_{\text{VICAD|construction}}\approx 1-(1-P_{\text{unrecognized/construction}})(1-R_{VICAD}) -\left(1-(1-P_{\text{unrecognized/construction}})(1-R_{VICAD})-P_{\text{unrecognized/construction}}\right)\times\frac{P(D_{VICAD}<l, l\sim L)}{P(T_{AD}<l, l\sim L)}$$

If the scenario passing rate of the single vehicle is $P_{\text{unrecognized | construction}}$ = 90%, and the scenario recall rate is R_{VICAD} = 99%, then $P_{\text{VICAD | construction}}$ will be ≈ 99.87%.
If the scenario passing rate of the single vehicle is $P_{\text{unrecognized | construction}}$ = 99.8%, and the scenario recall rate of the edge computing is R_{VICAD} = 99.9%, then $P_{\text{VICAD | construction}}$ will be ≈ 99.9991%.

(3) Profit assessment analysis:
The benefits of vehicle-infrastructure cooperative decision planning for autonomous driving are significant, as shown in Table 3.9:

1) The encounter probability of vehicle scenarios is significantly reduced: Through vehicle-infrastructure cooperative routing, decision-making, and planning, vehicles can avoid encountering construction scenarios in various ways. In the case of R_{VICAD} = 99.9%, the scenario encounter frequency can be reduced from 4.5 times /10,000 km to 0.0270 times/10,000 km;
2) The scenario passing rate P of the vehicle has been significantly improved: In the case of $P_{\text{unrecognized | construction}}$ = 99.8%, R_{VICAD} = 99.9%, $P_{\text{VICAD | construction}}$ will reach the ideal value of 99.9991%, and the failure rate of the scenario will be reduced from 0.9 times/million km to 0.00405 times/million km.

Comparison item	Vehicle-infrastructure cooperative decision-making and planning link time/D VICAD	Scenario encounter frequency/M	Scenario success rate/P	
			Condition 1	Condition 2
Single-vehicle intelligent decision-making and control	-----	4.5 times/10,000 km	$P_{\text{AD | Change}}$ = 90% R_{VICAD} = 99%	$P_{\text{AD | Change}}$ = 99.8% R_{VICAD} = 99.9%
Vehicle-infrastructure cooperative decision-making and control	≤3min	0.0270 times/10,000 km (in case of R_{VICAD} = 99.9%)	99.87%	99.9991%

Table 3.9 Profit Analysis for VICAD Under Construction Scenario

3.2.2.2 Transforming from "Unsafe" to "Safe" through "environment control"

(I) Overall technical principle

Environment safety is also an important factor affecting the safety of autonomous driving. Through vehicle-infrastructure cooperation, "environment control" can be realized, and the coordination and unification of vehicle driving travel and traffic operation management can be achieved, thus improving the safety of autonomous driving. As shown in Figure 3.26, while infrastructure systems and facilities provide VICAD services for autonomous driving, they can also use infrastructure real-time high-precision perception and positioning capabilities, to monitor road and traffic operating conditions in real time and identify unsafe events and factors, taking effective measures to intervene and control traffic facilities in a timely manner, and issuing traffic environment information to vehicles in advance through mobile cellular networks or RSU communication equipment, thereby avoiding traffic accidents and improving traffic safety.

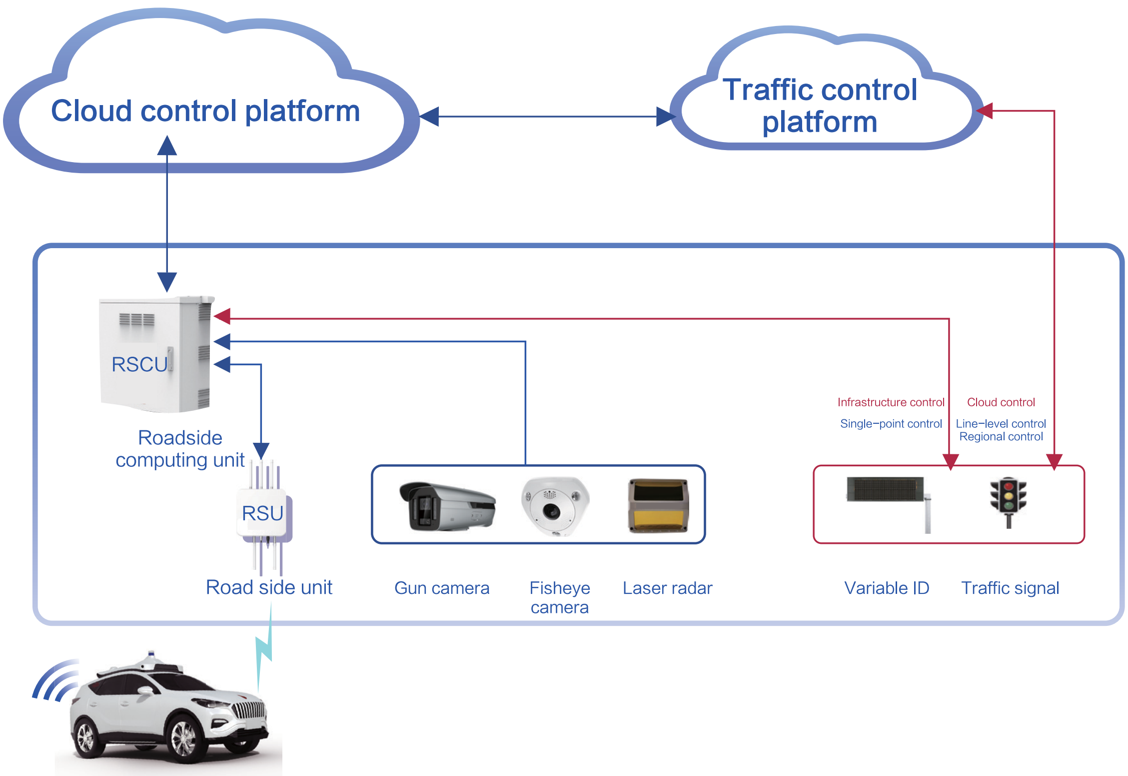


Figure 3.26 Technical Principles of Improving Autonomous Driving Safety with "Environment Control"

(II) Examples of typical scenarios

From an "environment control" perspective, two common scenarios are presented to improve the safety of autonomous driving. In both scenarios, the infrastructure plays a critical role in detecting and responding to potential risks.

(1) Management and control of water accumulation in the underpass road

Problem description:

Urban roads commonly feature underpasses that are prone to water accumulation during rainy weather, posing a significant risk to the safety of vehicles and pedestrians.

Scenario principle:

Figure 3.27 shows that the infrastructure can be equipped with water accumulation sensors that detect the depth of water accumulation in underpass roads. Based on the detected water depth, various methods can be employed to warn or control vehicles, including map reminders, V2X early warning, cloud-based routing change, traffic light control, and reporting to traffic management and urban management platforms.

Figure 3.27 Water Accumulation Scenario in Underpass Road

Application Benefits:
Figure 3.28 shows that the infrastructure system can control traffic lights or provide a road gate to prevent vehicles from entering dangerous areas, ensuring the safety of vehicles and personnel.

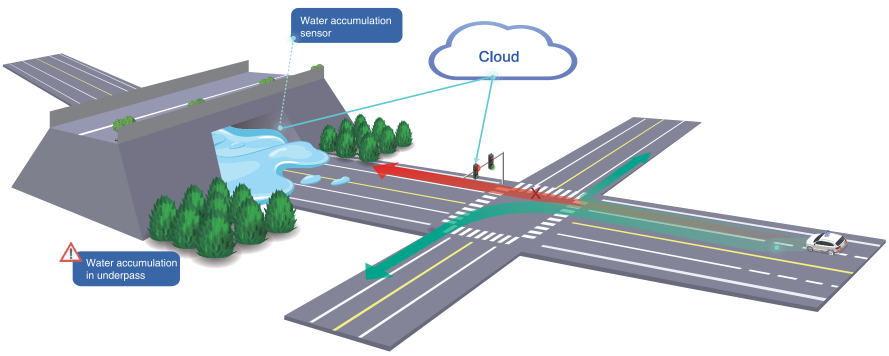


Figure 3.28 Safety Control for Water Accumulation in Underpass Road

(2) Management and control of dangerous events in the tunnel

Problem description:

As shown in Figure 3.29, if dangerous events occur in tunnels, such as fires, gas leaks, collapses, or accidents, the autonomous vehicle cannot obtain event information in advance, and once it enters the tunnel, a secondary accident may occur.

Figure 3.29 Traffic Accidents in Tunnel

Scenario principle:

Figure 3.29 illustrates that dangerous events in tunnels can be detected through the infrastructure's perception system. The perception system in the tunnel can be connected with signal control equipment at the tunnel entrance to prevent vehicles from entering the tunnel by controlling traffic lights or broadcasting tunnel events to vehicles through V2X.

Application Benefits:

Figure 3.30 shows that by controlling traffic lights, secondary traffic accidents can be avoided, ensuring personal and traffic safety.

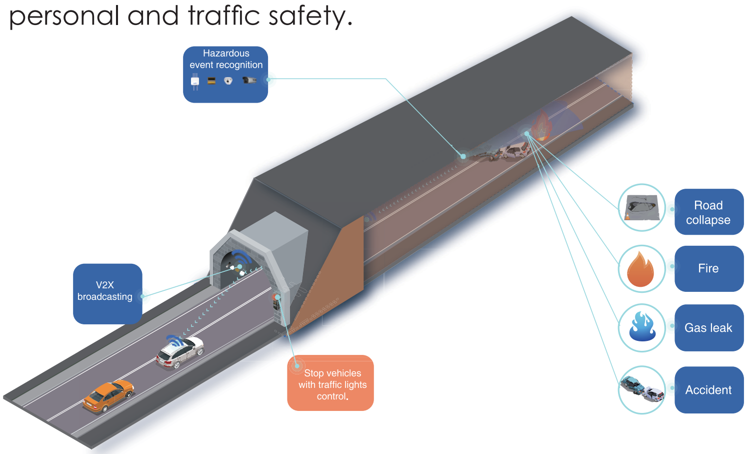


Figure 3.30 Safety Management and Control for Dangerous Situations in Tunnel

3.2.3 VICAD Safety Evaluation Model and Simulation Verification

In order to quantify and evaluate the safety benefits of VICAD in typical traffic scenarios, in this white paper, the complex traffic scenario interaction and high-fidelity sensor data rendering are incorporated into the Vehicle-Infrastructure Cooperated Autonomous Driving Safety Revenue Model (VICAD-SRM)[28] . This allows for the establishment of a Unified Model of Autonomous Driving Evaluation (UMADE). As illustrated in Figure 3.31, UMADE enables the selection of various test scenarios, traffic interaction methods, and evaluation metrics, facilitating quantitative comparative testing of system performance across different autonomous driving solutions.

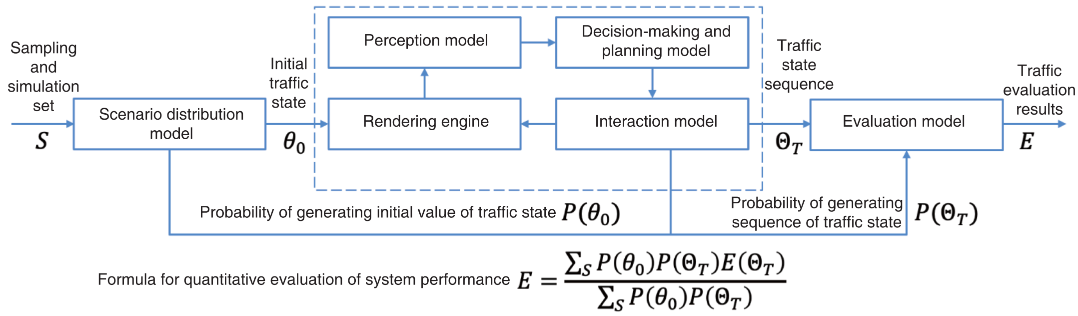


Figure 3.31 Unified Model of Autonomous Driving Evaluation (UMADE)

The following is a brief introduction to each functional module in the Unified Model of Autonomous Driving Evaluation.

1) Scenario distribution model is used to describe the distribution probability of the initial value of the traffic state in the selected scenario. Common distribution probability models include the log-normal distribution for the speed of the following vehicle, and the negative exponential distribution for the time headway of the following car, etc.

2) Rendering engine is used to provide high-fidelity sensor data for autonomous vehicles and road infrastructure devices based on the traffic state and to visualize and restore behavioral events in traffic scenes. The Unified Model of Autonomous Driving Evaluation (UMADE) is developed based on the open-source autonomous driving simulator CARLA using the UE4 rendering engine which provides data interfaces for common vehicle-mounted sensors including LiDAR and visual cameras, as well as roadside perception devices.

3) Interaction model is used to describe the interaction behavior among traffic participants. The UMADE supports traffic participants' settings such as traffic signals, vehicles, pedestrians, and non-motorized vehicles, and further provides customized interfaces for the interaction among traffic participants based on the built-in interaction model in Carla.

4) Perception model is used to simulate the process of environmental perception through

28. For the Vehicle-Infrastructure Cooperated Autonomous Driving Safety Revenue Model (VICAD-SRM), see Key Technologies and Developing Prospect of Vehicle Infrastructure Cooperated Autonomous Driving (2021).

cloud-based information and sensor data from the on-board units and roadside ones for the VICAD system. The UMADE supports autonomous driving-related perception algorithms such as target detection, semantic segmentation, and anomaly detection, which can be freely accessed at both ends of the vehicle and infrastructure.

5) Decision-making and control model is used to simulate the decision-making, planning and control process of the VICAD system through cloud information and sensor data at the vehicles and infrastructures. The UMADE supports the deployment of cooperative decision-making and control algorithms at both the vehicles and infrastructures, which further supports the scheduling of relevant traffic signals and vehicles in the traffic scenes in an orderly manner.

6) Evaluation model is used to evaluate the system performance of autonomous driving in traffic environments. The UMADE supports the selection of different evaluation methods and the quantitative evaluation of the safety and traffic efficiency indicators for specified autonomous driving schemes in specified traffic scenes.

In order to effectively illustrate the practical difficulties encountered in the implementation of autonomous driving, four typical scenarios were selected based on the analysis of publicly available data in the field of autonomous driving and Baidu's actual test data, namely pedestrian ‘blind zone’, turning left without protection, anomalous obstacles and abnormal traffic conditions (see Table 3.10 for details). These scenarios represent the safety issues and edge scenarios that are highly concerned in the field of autonomous driving. The UNMAD is used for quantitative evaluation.

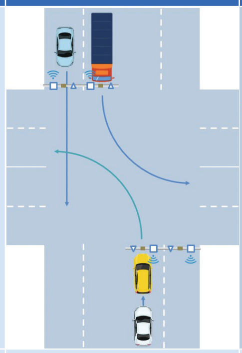
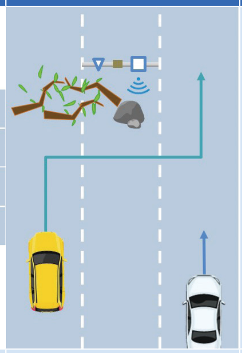
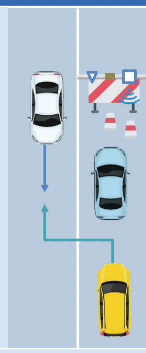
Scenarios	Pedestrian ‘blind zone’	Turning left without protection	Anomalous obstacles	Abnormal traffic conditions
Scenarios description				
Scenarios parameter	Ego vehicle speed Following vehicle speed Distance between ego and following vehicles	Ego vehicle speed Following vehicle speed Oncoming vehicle speed Distance between ego and following vehicles	Ego vehicle speed Following vehicle speed Entry time of following vehicle	Ego vehicle speed Following vehicle speed Entry time of following vehicle

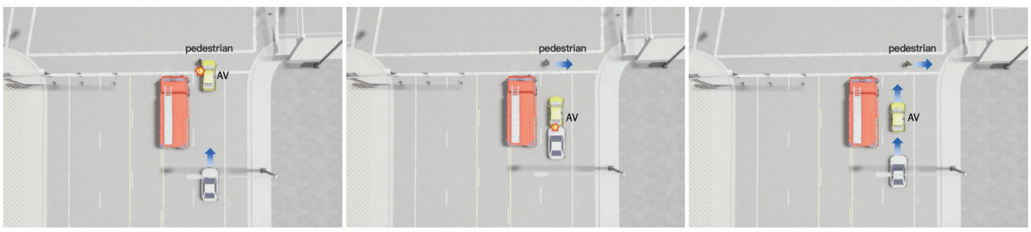
Table 3.10 Scenario List

Transportation participants	Roadside infrastructure, vehicles and pedestrians	Roadside infrastructure, vehicles	Roadside infrastructure, vehicles	Roadside infrastructure, vehicles and road construction signs
Collaborative perception	Complementary perception	Complementary perception	Redundant/ Enhanced perception	Enhanced perception
Collaborative decision-making and control	Collaborative braking of vehicles in the same direction	Collaborative braking of vehicles in the same direction	Collaborative obstacle bypassing of vehicles in the same direction	Collaborative yield of vehicles in the opposite direction
Key algorithms	Collaborative perception, Cooperative decision-making and control	Collaborative perception, Cooperative decision-making and control	Collaborative anomaly detection, Cooperative decision-making and control	Collaborative prediction and imitation, Cooperative decision-making and control
Evaluation methods	Collision probability, Pedestrian casulty probability, Traffic efficiency	Collision probability, Traffic efficiency	Collision probability, Traffic efficiency	Traffic capacity, Traffic efficiency

For the above-mentioned typical traffic scenarios, three different autonomous driving modes of single-vehicle intelligence, vehicle-infrastructure cooperative perception, and vehicle-infrastructure cooperative decision-making and control can be selected for system performance comparison, and the following simulative analysis results can be obtained using the UMADE.

(1) Pedestrian ‘blind zone’

As shown in Figure 3.32, single-vehicle intelligence cannot effectively perceive blind spots caused by occlusion, which leads to a serious traffic safety hazard. In contrast, vehicle-infrastructure cooperative perception provides complementary information and improves the perception of information for the leading ego vehicle to avoid pedestrians. The vehicle-infrastructure-cloud cooperative decision-making and control provides the ability for global collaborative decision-making of all vehicles in the scene, which provides the following vehicle with complementary information on the driving behavior of the leading vehicle, thereby reducing the probability of collision events.



Single-vehicle intelligence: Due to visual obstruction, the leading vehicle may have difficulty timely avoiding pedestrians.

Collaborative perception: The leading vehicle brakes to avoid pedestrians, but the following vehicle may have a risk of rear-end collision.

Vehicle-infrastructure-cloud integration: The leading and following vehicles collaborate to avoid pedestrians and pass through safely.

Figure 3.32 System Performance Comparison Based on Pedestrian ‘Blind Zone’ Scenario

(2) Turning left without protection

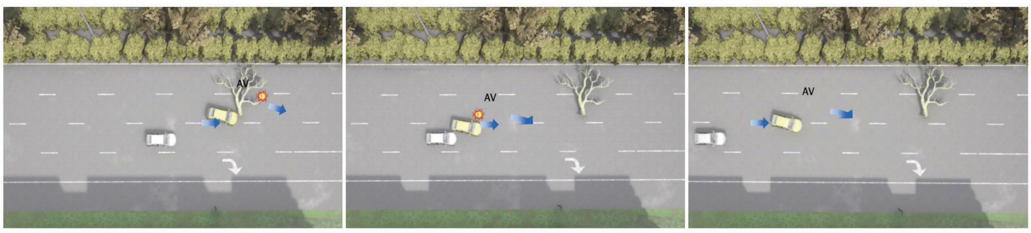
As shown in Figure 3.33, since the large vehicle turning left blocks the leading ego vehicle's perception field of view, the leading vehicle cannot effectively perceive the straight-driving vehicle in the opposite direction only by relying on the single-vehicle intelligence, resulting in a high traffic safety risk. Similar to the pedestrian 'blind zone' scenario, the vehicle-infrastructure cooperative perception provides complementary information, delivering information gain for the leading vehicle to avoid the oncoming vehicle in the opposite direction. The cooperative decision-making and control support the cooperative decision-making of all vehicles in the scene, and provide the information gain on the driving behavior of the preceding vehicle for the following vehicle, thus reducing the probability of collision events.

Single-vehicle intelligence: The ego vehicle has the risk of colliding with the oncoming vehicle in the opposite direction. | Collaborative perception: The host vehicle brakes to avoid the vehicle in the opposite direction, and the following vehicle has the risk of | Vehicle-infrastructure-cloud integration: The ego vehicle and the following vehicle coordinate to pass through the intersection.

Figure 3.33 System Performance Comparison Based on Unprotected Turn-left Scenario

(3) Anomalous obstacles

Anomalous obstacles generally do not appear in the training samples of the autonomous driving perception system, and an additional perception anomaly detection algorithm is required to perform perception uncertainty analysis, to convert the "unknown" scenarios in the Safety of The Intended Functionality (SOTIF) into a "known" abnormal scenario. As shown in Figure 3.34, single-vehicle intelligence fails to effectively detect anomalous obstacles in advance, and there are serious traffic safety hazards. The vehicle-infrastructure cooperative perception provides redundant and enhanced information, delivering information gain for the vehicle in front to avoid abnormal obstacles. The vehicle-infrastructure-cloud cooperative system supports the cooperative decision-making ability of all vehicles in the scene, and provides information gain on the driving behavior of the leading vehicle for the following vehicle, reducing the probability of collisions.

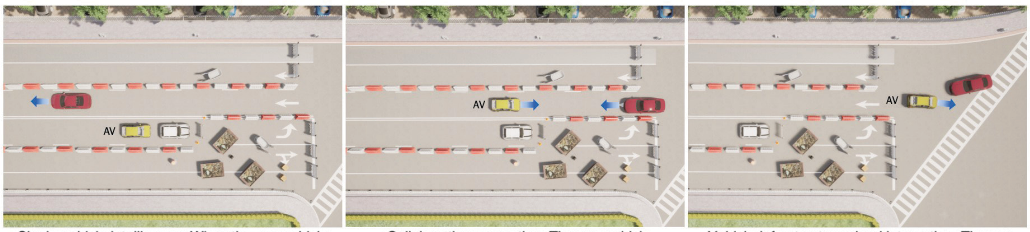


Single-vehicle intelligence: It is difficult for the ego vehicle to timely avoid anomalous obstacles. | Collaborative perception: The ego vehicle changes lanes earlier to avoid anomalous objects, and the following vehicle has a risk of | Vehicle-infrastructure-cloud integration: The leading vehicle and the following vehicle cooperate to avoid anomalous obstacles and

Figure 3.34 System Performance Comparison Based on Anomalous Obstacles Scenario

(4) Abnormal traffic conditions

In the scenario shown in Figure 3.35, autonomous vehicles face more complex traffic conditions. First of all, a stationary vehicle parks in front of the road construction zone, and the autonomous vehicle needs to judge its driving intention and determine the queuing strategy. Secondly, a road section (two-way single lane) is under temporary construction, the autonomous vehicle needs to decide whether to violate the traffic rules and "retrograde". Finally, a vehicle drives in the opposite direction on a single-lane road, the autonomous vehicle needs to game and interact with the vehicle. Due to the lack of global information, it is difficult for single-vehicle intelligence to make effective decisions in this complex situation. The vehicle-infrastructure cooperative perception, however, provides redundant and enhanced incremental information, effectively predicting the intention of stationary vehicles, imitating the driving behavior of other non-autonomous vehicles learned through long-term observation of the roadside infrastructure, and enabling making effective decisions in the aforementioned complex situations. The vehicle-infrastructure-cloud cooperative system can obtain prior information on abnormal traffic conditions in the cloud server. Combined with the capacity of cooperative decision-making of all vehicles in the scene, it provides the oncoming vehicle with information gain such as the driving intention of the autonomous vehicle, thereby improving the passing efficiency in case of single-lane traffic in opposite directions.



Single-vehicle intelligence: When the ego vehicle encounters a stationary vehicle ahead, it is difficult to make effective decisions.

Collaborative perception: The ego vehicle imitates other vehicles to detour in the opposite direction, and meets the opposite vehicle in the single lane.

Vehicle-infrastructure-cloud integration: The ego vehicle imitates other vehicles to detour in the opposite direction, and the opposite vehicle obtains the driving intention of the ego vehicle,

Figure 3.35 System Performance Comparison Based on Abnormal Traffic Conditions

In general, vehicle-infrastructure cooperative perception and vehicle-infrastructure-cloud cooperative decision-making and control have significantly improved the safety of autonomous driving. The above typical scenarios are extreme scenarios with a low probability of occurrence and are highly dangerous. Pedestrians are a vulnerable group in traffic safety issues, and ensuring pedestrian safety is particularly important for the development and application of autonomous driving technology. In the extreme scenario of pedestrian ‘blind zone’, compared with AD mode, the VICAD mode greatly improves the safety in terms of human injury evaluation indicators. Moreover, the experimental results show that VICAD significantly improves the system performance in dealing with the scenarios of unprotected left turn, anomalous obstacles, and abnormal traffic conditions, proving that VICAD can effectively help solve problems faced by autonomous driving vehicles in extreme scenarios. The detailed experimental data are as shown in Table 3.11, and the detailed experimental methods can be found in Appendix B.

Scenarios	Pedestrian 'blind zone'			Unprotected left turn		Anomalous obstacles		Abnormal traffic	
Evaluation model	Driving collision rate	Pedestrian casualty rate	Traffic efficiency in the extreme scenario	Driving collision rate	Traffic efficiency in the extreme scenario	Driving collision rate	Traffic efficiency in the extreme scenario	Traffic capacity	Traffic efficiency in the extreme scenario
Single-vehicle intelligence	3.30×10^{-5}	6.85×10^{-6}	1881.51s	3.10×10^{-5}	201.30s	5.30×10^{-5}	359.98s	None	N/A
Vehicle-infrastructure cooperative perception	2.95×10^{-6}	9.22×10^{-8}	119.13s	1.04×10^{-5}	71.25s	1.05×10^{-5}	80.02s	Available	10.504s
Vehicle-infrastructure cooperative decision-making and control	6.93×10^{-7}	4.78×10^{-8}	50.52s	9.26×10^{-6}	64.84s	0	10.39s	Available	7.143s

Table 3.11 Experimental Results Based on UMADE

3.3 VICAD Expands ODD for Continuous Operation

3.3.1 Restrictions on ODD of Autonomous Driving

The ODD of autonomous driving is the set of external environmental conditions within which the autonomous vehicle is designed to operate safely and effectively. If any of the preconditions within the ODD are not met, the autonomous driving system may fail, and either the driver must take over or emergency stop measures must be initiated. Figure 3.36 illustrates the ODD restrictions for different levels of autonomous vehicles, with L4 having the fewest restrictions, followed by L3, and L2 having the strictest limitations, as it can only be used in specific environments or scenarios.

For instance, consider an L3 level autonomous driving ODD. The autonomous driving mode is only permitted when the following conditions are satisfied:

1) The vehicle is driving on an expressway or a road designated for motor vehicles with a central isolation belt and guardrails, containing at least two lanes.

2) The distance between the vehicle and the surrounding lanes is relatively small, as in a state of traffic congestion.

3) The vehicle's speed does not exceed 60 km/h.

4) No pedestrians or traffic lights are present within the detectable range of the sensor.

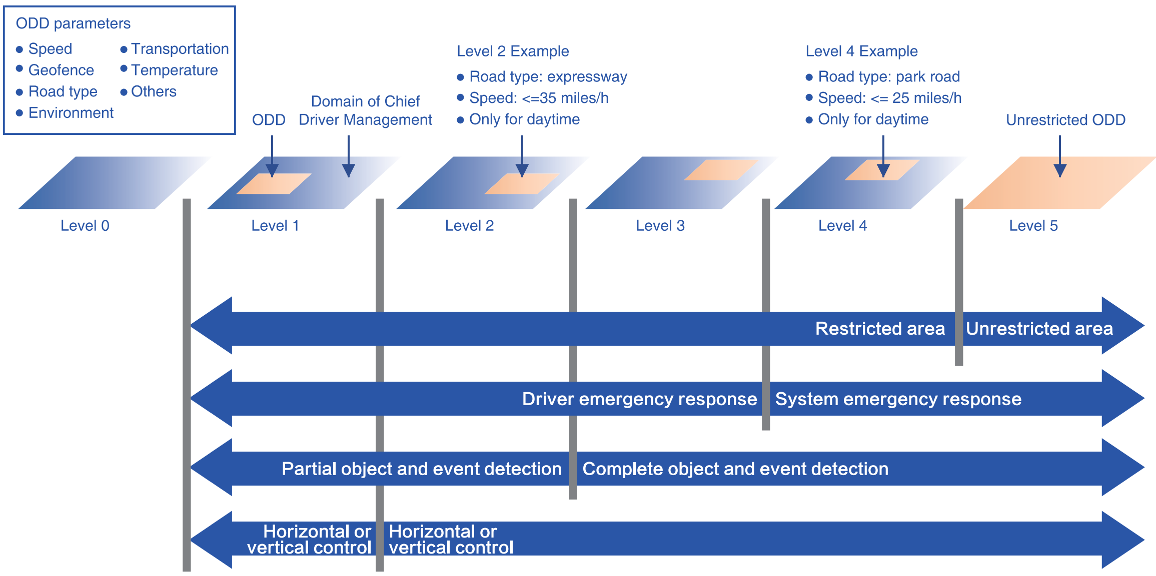


Figure 3.36 ODD Restrictions of Autonomous Driving at Different Levels

As depicted in Figure 3.37, the ODD for autonomous driving can be categorized into three groups: static entities, environmental conditions, and dynamic entities[29].

1) Static entities refer to the entities whose state does not change in the operating environment, such as roads, buildings, etc.

2) Environmental conditions encompass weather, atmospheric conditions, and information environment.

3) Dynamic entities consist of entities whose operational states change, such as traffic conditions, road users, and non-road users.

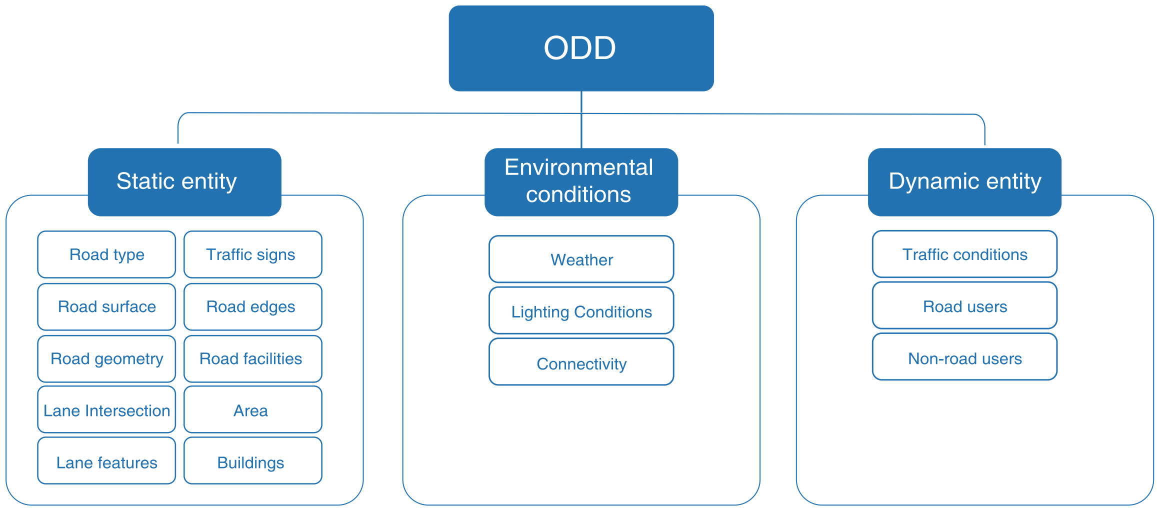


Figure 3.37 ODD Classification of Autonomous Driving

29. Refer to the White Paper on Design and Operation of Autonomous Driving issued by the National Technical Committee of Auto Standardization.

3.3.2 Dynamic Management and Expansion of ODD through VICAD

(I) Overall technical principle

The ODD of autonomous driving can be dynamically managed and expanded through vehicle-infrastructure cooperation, allowing autonomous vehicles to achieve continuous autonomous driving in a wider range of environments. The process of expanding ODD through VICAD management involves the following steps:

1) Clarification of ODD restricted scenarios for different grades, brands, and models of autonomous vehicles;

2) Real-time detection and identification of ODD restricted scenarios through vehicle-infrastructure cooperative perception;

3) Initiation of VICAD application services by the infrastructure for impacted ODD scenarios;

4) Safe passage through ODD restricted scenarios with the help of infrastructure.

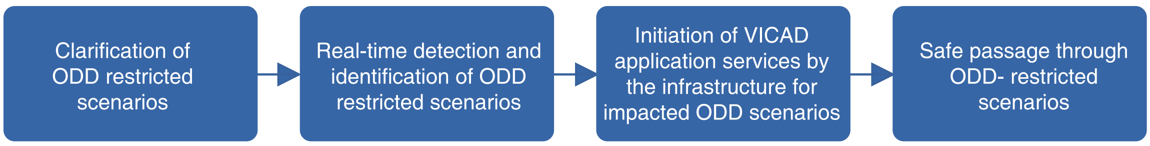


Figure 3.38 ODD Dynamic Management Flow Chart

(II) Example Scenario: Coordinated Passage at Non-Signalized Intersection

Table 3.12 presents a comprehensive list of typical ODD restriction scenarios that are likely to exist in Level 4 autonomous driving, such as road construction, traffic accidents, mixed traffic, and other related scenarios. To address dynamic entity-like ODD restrictions, such as coordinated passage at an intersection without traffic lights, the perception and decision-making capabilities of CAVs can be improved through vehicle-infrastructure cooperative perception, decision-making and planning. This will ultimately lead to the lifting of ODD restrictions. In the case of static entities and environmental condition-like ODD restrictions, vehicle-infrastructure cooperative control can be used to achieve optimal control of vehicles, traffic facilities, and traffic environments, such as optimal control of traffic lights, road snow melting and deicing, and other devices. This will ensure that vehicles can safely pass through ODD restricted scenarios.

ODD Restriction Scenario Classification			Typical scenarios	L4 Autonomous Driving Scenario Response Capability	Ways to Expand ODD
Primary classification	Secondary classification	Tertiary classification			
Dynamic entity	Traffic conditions	Interactive conflict	Interaction conflict between motor vehicles: sudden behaviors such as merging conflicts, sudden braking of the front vehicle, cutting in, and turning sharply.	Poor	Vehicle-infrastructure cooperative perception/ decision-making/ planning
		Traffic congestion	Vehicle stagnation	Poor	
			Vehicle queuing or congested	Poor	
	Road users	Motor vehicle	Dangerous behaviors: overspeed, retrograde, running red lights and other sudden actions	Poor	
		Pedestrian	Dangerous behaviors: pedestrians entering the motorway, blind zone, running red lights, and other sudden actions	Poor	
		Non-motorized vehicle	Dangerous behaviors: non-motorized vehicles entering motor vehicle lanes, blind zone, overspeed, retrograde, running red lights and other sudden actions	Poor	
	Non-road users	Animal	Animal intrusion and other unexpected behaviors	Poor	
		Others	Low obstacles, littering, abnormal obstacles, etc.	Poor	
Static entity	Road type	Parking lot	Indoor parking lot	Poor	
	Road surface	Road pavement	Water accumulation, freezing, snow, muddy, etc.	Poor	Vehicle-infrastructure cooperative control (environment control)
	Lane crossing	At-grade intersection	Intersection with signal control unit	Poor	Vehicle-infrastructure cooperative perception/ decision-making/ planning
			Intersection without signal control unit	Poor	
			Ramp diversion and merging, and turnoff	Poor	
			Roundabout	Poor	

Static entity	Lane	Lane	Unclear lane line	Poor	Vehicle-infrastructure cooperative control (environment control)
	features	marking	Without lane line	Poor	
	Road Boundary	Boundary line	Without road boundary line	Poor	
	Road facilities	Special facilities	Long tunnel	Poor	Vehicle-infrastructure cooperative perception / decision-making / planning / control (vehicle control)
			Bridge	Poor	
			Overpass	Poor	
			Railway crossing	Poor	
		Temporary facilities	Road construction	Poor	
			Traffic accident	Poor	
Environmental conditions	Weather	Visibility	Poor (heavy fog, heavy snow, heavy rain, sandstorm, agglomerate fog, etc.)	Poor	Vehicle-infrastructure cooperative control (environment control)
	Connectivity	Signal intensity	Signal interference	Poor	
				Poor	

Table 3.12 Implementation Methods of ODD Restriction and Management Extension for Autonomous Driving (Example)

The coordinated traffic at a non-signalized intersection is used as an example to illustrate the management and expansion of ODD.

Problem description:

Taking Figure 3.39 as an example, when autonomous vehicles navigate through complex intersections, such as those found in cities, expressways, or expressway ramp intersections, or intersections without traffic lights, collision risks and takeovers are likely to occur due to cross conflicts of vehicle flows in different directions.

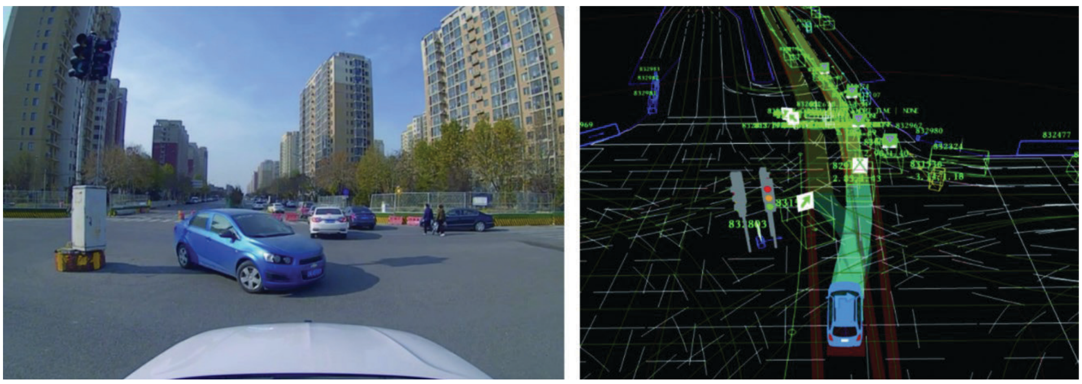


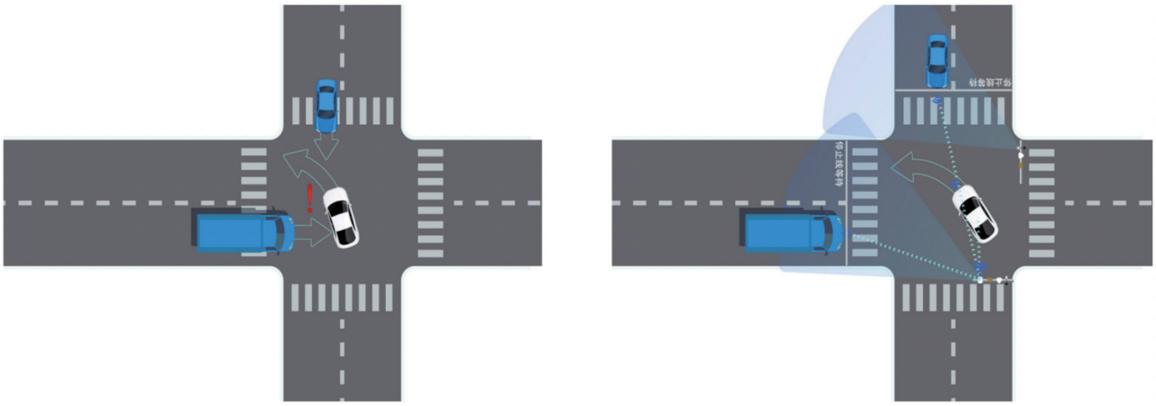
Figure 3.39 Intersection Scenario without Traffic lights

Scenario principle:

To mitigate these risks, vehicle-infrastructure coordination can be implemented to identify and predict the driving intentions of all vehicles from the intersection's perspective and formulate appropriate traffic strategies to ensure orderly passage and avoid takeovers. This involves roadside systems and facilities performing real-time perception predictions on intersection vehicles, and intersection vehicles actively reporting their driving intentions, including expected trajectory (vehicle position and speed at each moment) through V2X. Based on traffic rules and priority strategies, such as allowing straight-driving vehicles to pass first and left-turning vehicles to pass later, integrated decisions are made by roadside systems and facilities. Left-turning vehicles slow down and avoid in advance according to the unified dispatch at the infrastructure, and straight-driving vehicles may pass without slowing down or accelerating. Ultimately, all vehicles pass through the intersection efficiently under the unified dispatch at the infrastructure.

Application Benefits:

Through cooperative perception, decision-making and planning, it can be guaranteed that autonomous vehicles have the ability to navigate through cross-road environments without takeovers, thus expanding the ODD of self-driving. The application of this approach is shown in Figure 3.40.



Autonomous vehicles encounter challenges in safely and efficiently navigating unsignalized intersections, thereby necessitating human intervention.

The cooperative passage of autonomous vehicles at unsignalized intersections is made possible by the synchronized management of both vehicle and infrastructure control systems.

Figure 3.40 The collaborative decision-making and planning between vehicle and infrastructure systems enables the coordinated flow of traffic at unsignalized intersections.

(III) Comprehensive Application Benefits

Figures 3.41 and 3.42 demonstrate the comparative effect of vehicle-infrastructure coordination on the expansion of autonomous driving ODD before and after implementation. Specifically, a variety of scenarios are encountered during a typical travel itinerary, including parking scenarios such as navigating indoor parking areas, traffic conflicts on urban roads such as intersections with traffic lights, mixed pedestrian and non-motorized vehicle roads, and situations such as long tunnels on expressways, low-visibility areas like sand, dust, and fog, and construction zones.

Due to the limitations of the ODD of autonomous driving, the vehicle must exit autonomous driving mode when encountering challenging scenarios, and the driver must take control of the vehicle. This interruption prevents continuous autonomous driving. However, with the assistance of VICAD, the vehicle can maintain autonomous driving in these restricted ODD scenarios, allowing for uninterrupted autonomous driving (excluding uncontrollable factors such as extreme weather conditions or insufficient HD map coverage), as depicted in Figure 3.42.

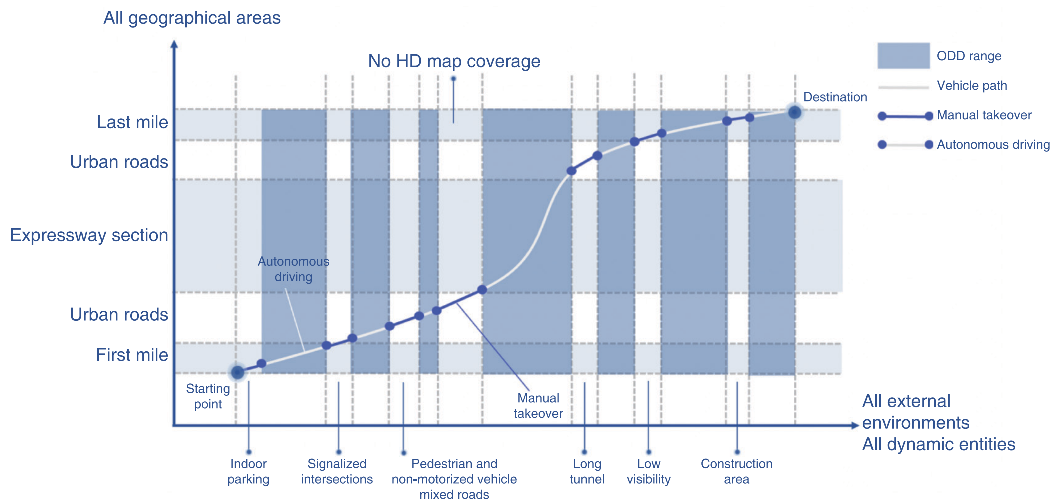


Figure 3.41 Before ODD Extension

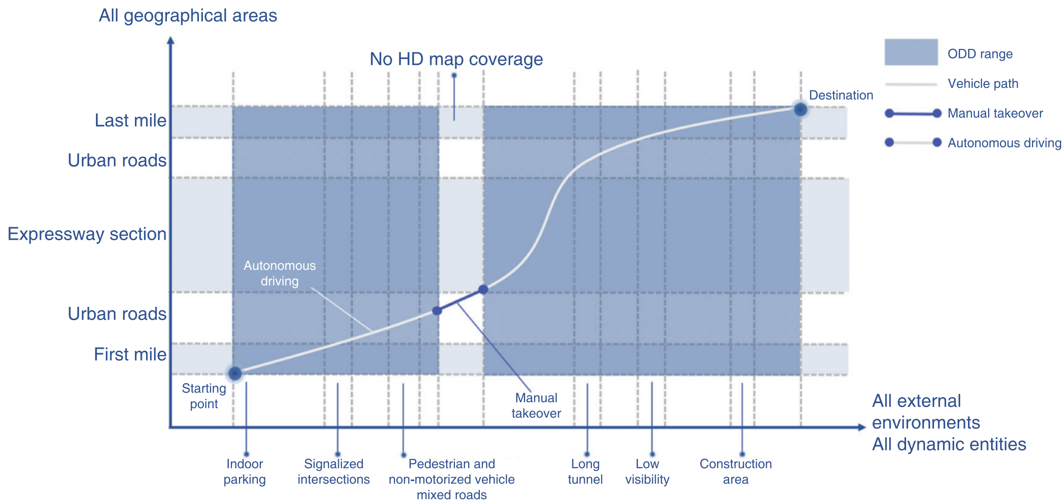


Figure 3.42 After ODD Extension

3.4
Brief Summary

The previous discussion highlights the multifaceted functions of VICAD in providing differentiated application support services for L4 autonomous vehicles. This technology can enhance the safety and universality of L4 autonomous vehicles, thereby serving the daily transportation needs of residents. Figure 3.43 illustrates the impact of VICAD on L4 autonomous vehicles, with the following observations:

1) VICAD can significantly improve the level and capability of L4 autonomous driving, enabling it to cope with various complex scenarios.

2) At present, L4 autonomous driving can only be commercialized in a closed or limited area. However, with sufficient research and development investment, L4 single-vehicle intelligence can be achieved, leading to large-scale commercialization of driverless autonomous driving. VICAD can play a critical role in accelerating the achievement of this goal.

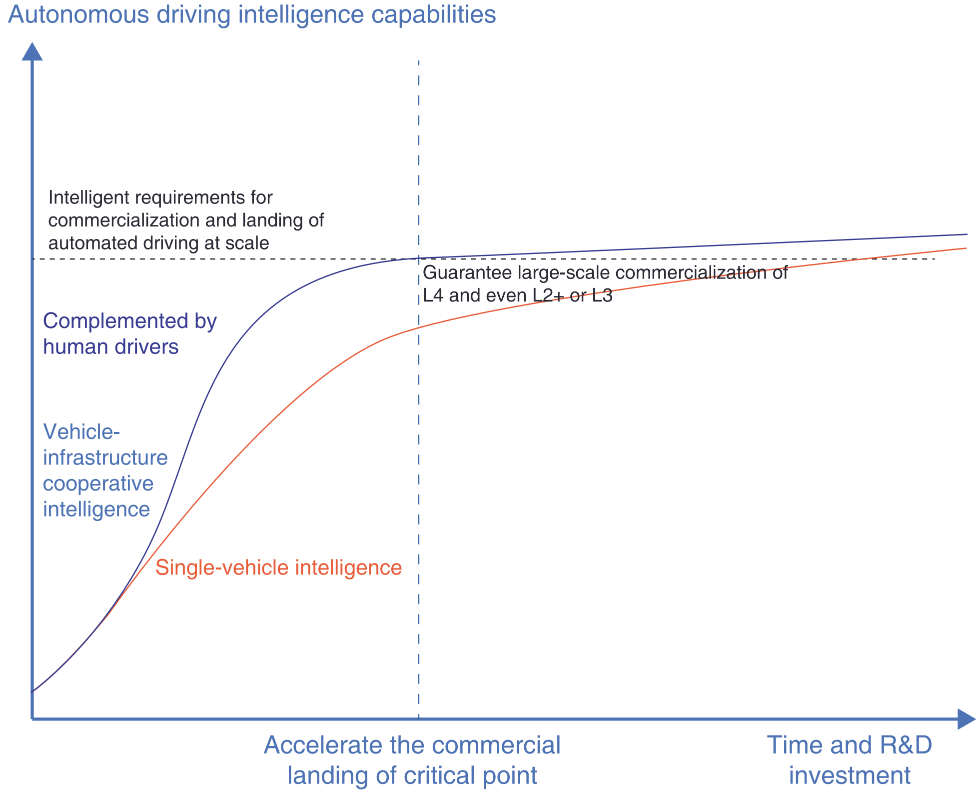


Figure 3.43 Role of VICAD in Promoting L4 Autonomous Driving

04

VICAD Accelerates the Commercialization of Level 2 Autonomous Driving

The deployment of L2 autonomous driving has reached a significant milestone, marked by its extensive commercialization and impressive growth trajectory. Despite these advancements, the technology is not without its challenges, including a high incidence of safety concerns and limited functional applicability. To address these issues, VICAD has emerged as a solution tailored for L2 autonomous vehicles, leveraging multi-access and multi-level services to elevate L2 to a new stage of large-scale commercialization. This approach promises to greatly enhance both safety and user experience.

4.1
Solutions and Challenges of L2 Autonomous Driving

As per the definition outlined in the SAE standard, Level 2 (L2) autonomous driving technology facilitates the control of steering and speed, while necessitating continuous participation from the driver, who must be prepared to intervene and assume control in emergency situations. L2+ is an informal nomenclature employed by various manufacturers in the industry to underscore the extent of enhancement offered by their products over the baseline L2 functionality. Variations such as L2.5 and L2++ also belong to this category. In all such cases, the driver remains the primary entity responsible for the vehicle's operation and must maintain vigilance throughout the driving experience, ready to resume control when required, thus aligning with L2 requirements. For the purposes of this white paper, we will use the term L2 to refer to these types of products.

4.1.1 Common L2 Technical Solutions

Currently, there are three commonly adopted technical solutions for Level 2 (L2) autonomous driving based on the sensor layout. These solutions are the 1R1V (3R1V) solution, 5R1V (5R5V) solution, and 1R8V solution, where R represents the millimeter-wave radar and V represents the camera.

(1) 1R1V (3R1V) solution

As shown in Figure 4.1, the 1R1V (3R1V) solution is the most mature and widely adopted solution. It consists of a single vision module FCM and a single radar module FCR, without a separate centralized controller. The FCM module is responsible for visual perception, while the FCR module handles radar perception. For sensor fusion, a post-fusion solution is employed. The 3R1V solution is an extension of 1R1V, with the addition of two rear radars to provide highway assistance (HWA) in a partial speed range of action.

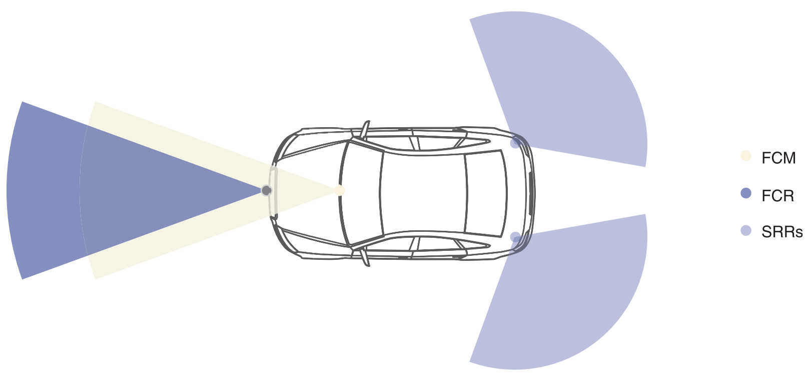


Figure 4.1 1R1V Solution

(2) 5R1V (5R5V) solution

As shown in Figure 4.2, the 5R1V (5R5V) solution is an extension of 1R1V, where four corner radars are added. The centralized domain controller (DCU) is still a low computing power MCU, which fuses structured sensor data and controls the vehicle. The 5R5V solution can be formed by adding four surround-view cameras to the 5R1V solution. In this solution, a centralized domain controller is integrated, supporting highway pilot (HWP) in the full speed range of action.

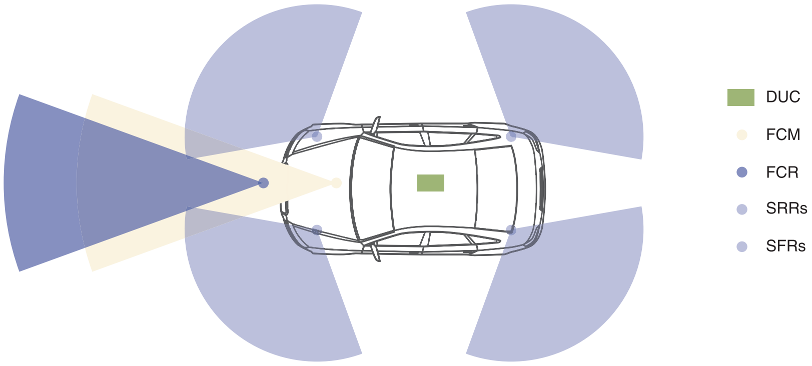


Figure 4.2 5R1V Solution

(3) 1R8V solution

As shown in Figure 4.3, the 1R8V solution includes FCR, forward tri-cameras, four side cameras, and one rear camera, which support navigation on a pilot and are equipped with an HD map. The DCU is generally upgraded to a computing platform with high computing power, and most sensors are changed from smart sensors to raw sensor data output, which is processed and fused on the computing platform. This solution offers advanced capabilities for autonomous driving, with more comprehensive sensor coverage and high computing power.

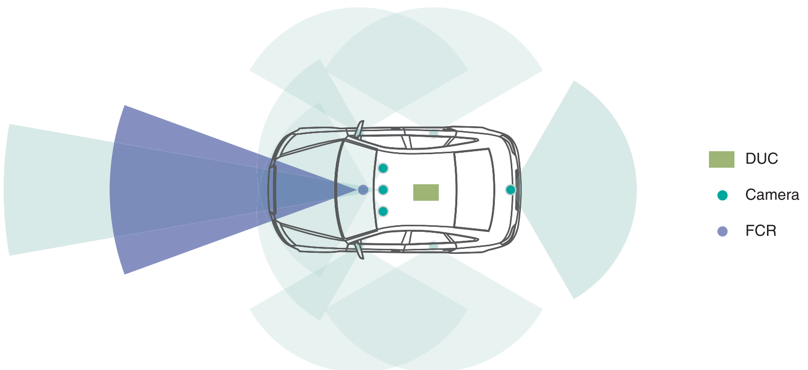


Figure 4.3 1R8V Solution

4.1.2 Evolution of Electrical and Electronic Architecture

The electrical and electronic architecture of intelligent driving has been undergoing constant development and evolution. As depicted in Figure 4.4, the computing platform and the vehicle sensor solution have been evolving from L1 to L4, with an increasing degree of centralization.

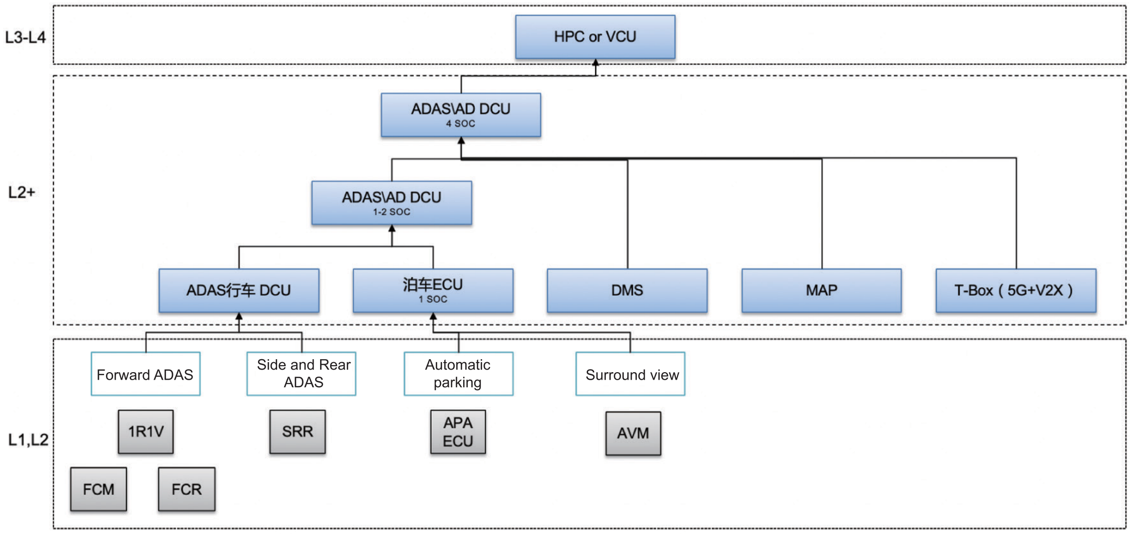


Figure 4.1.4.4 Evolution of Electrical and Electronic Architecture in Vehicle

In comparison to Section 4.1.1, the 1R1V solution does not involve a central controller, and instead uses the FCM or FCR module for sensor fusion and vehicle control. This solution adopts a post-fusion plan, which requires low computing power and simple logic for planning and control, making it suitable for simple operating conditions on high-speed structured roads.

As the number of sensors increases and complex deep learning models for perception are introduced, the complexity of sensor fusion, perception, prediction, planning, and control increases from 5R1V. L2 vehicles have now started to be equipped with centralized computing platforms, high-definition maps, high-accuracy positioning, and on-board communication units, enabling them to navigate on high-capacity roads.

As L2 further develops, the in-vehicle computing platform integrates communication capabilities along with positioning, maps, and single-vehicle perception. This integration supports vehicle-vehicle, vehicle-infrastructure, and vehicle-cloud communication, thus strongly guaranteeing cooperative positioning, perception, decision-making, planning, and control in terms of hardware and software architecture.

4.1.3 Challenges of L2 Autonomous Driving

As with the issues faced by L4 autonomous driving discussed in Chapter 3, the challenges confronting L2 autonomous driving are especially notable with respect to safety and ODD limitations. Specifically, in terms of safety, L2 autonomous driving remains in the stage of human-machine co-driving, wherein the driver bears primary responsibility. Consequently, it is imperative to incorporate infrastructure perception and infrastructure safety event reminders into vehicle decision-making and planning, and to prioritize human-driver interaction to ensure sufficient lead time for takeover, reduce the unexpectedness of takeover, and enhance the safety and intelligence of Level 2 autonomous driving.

This underscores the need for continued attention and investment in research and development to address the challenges impeding the advancement and implementation of L2 autonomous driving, with a focus on enhancing the cohesiveness of human-machine systems to improve safety and expand the ODD.

4.1.3.1 Safety challenges

As depicted in Figure 4.5, safety incidents involving L2 ADAS reveal that over 10% of such incidents result in traffic accidents that pose risks to personal safety, exceeding the rate observed in traditional manual driving. The top four causes of such accidents include:

1) Inadequate perception of hazards, disruptions, or roadwork ahead in a timely manner;
2) Failure to promptly respond to the deceleration, abrupt stop, or lane changes of vehicles in front;
3) Adverse ADAS operating conditions, such as rainy or snowy road surfaces or dense fog, which may increase the vehicle's braking distance or sensor failure;
4) Inability to effectively detect debris, remnants, and other static objects on the highway.

As shown in Figure 4.5, among the L2 ADAS safety incidents, more than 10% are traffic accidents that endanger personal safety, which is much higher than that of manual driving. The causes of top-4 accidents include:

1) Failure to perceive the trouble, breakdown or construction ahead in time;
2) Failure to timely cope with the vehicle in front decelerating, stopping suddenly or cutting in line;
3) Abnormal ADAS operating environment conditions, such as road surface in rainy and snowy days and agglomerate fog, may lead to the increased vehicle braking distance or the sensor failure;
4) Failure to effectively identify the littering, leftovers and other static objects on the highway.

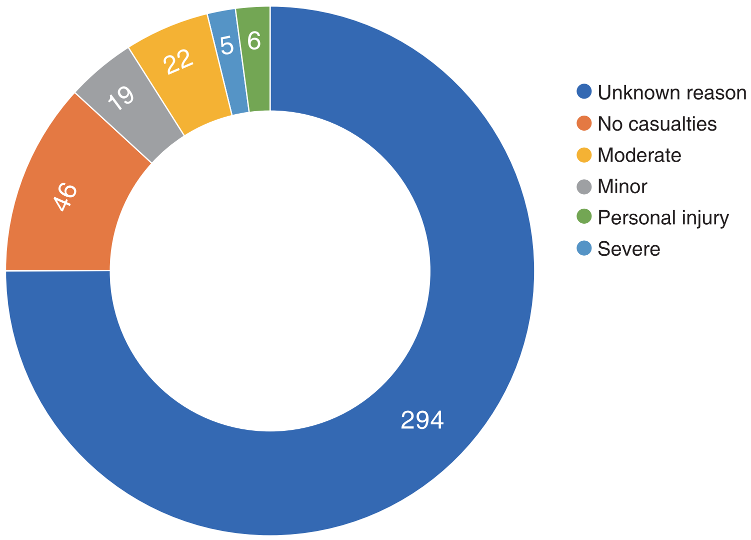


Figure 4.5 L2 ADAS Hazard Level Analysis (Data Source: NHTSA ADS SGO Report, June 2022)

(1) Conflict between perception distance and human response time

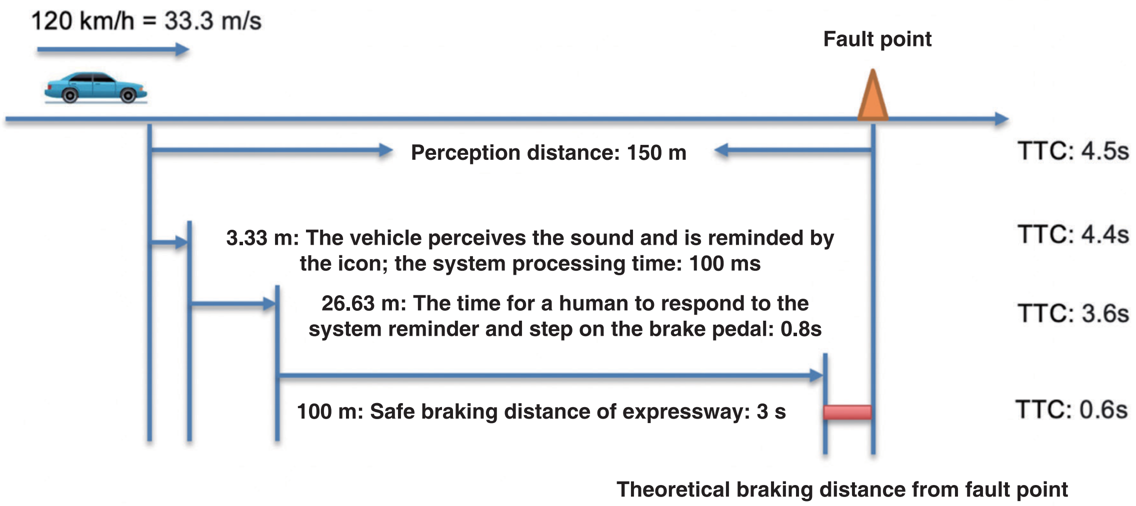
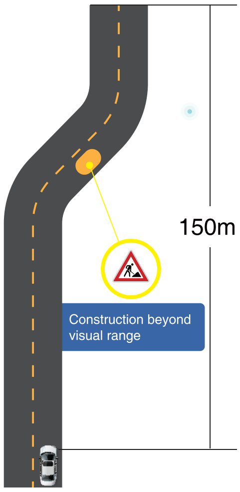


Figure 4.6 TTC Analysis of Expressway Construction Scenario

The discrepancy between perceived distance and human response time poses a significant risk to the safety of L2 ADAS on expressways. Predicting accidents, construction, and other safety events in advance is crucial for improving L2 ADAS safety. However, the limited time for response presents a challenge. For instance, in a typical scenario of roadblock recognition, as illustrated in Figure 4.6, when the vehicle is traveling at a speed of 120 km/h, the roadblock cone can be recognized at a distance of about 150 m. However, the final time to collision (TTC) is less than 1 s after driver warning and braking, leaving very limited safe response time. In scenarios with large road curvature or tunnels, as shown in Figure 4.7, L2 ADAS may not predict safety events, leaving drivers with no response time.



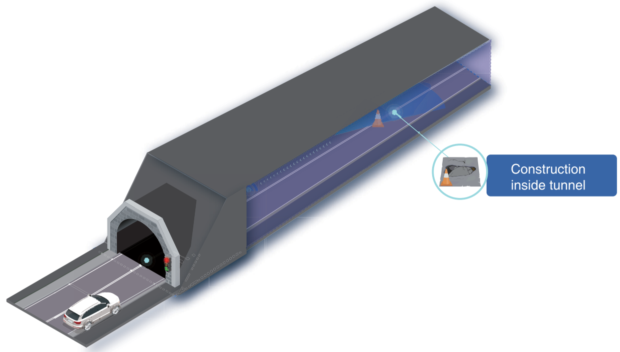


Figure 4.7 Perception Distance Affected by Road Environment

(2) Insufficient recognition capacity for static objects

L2 ADAS on expressways face challenges in recognizing static objects, such as roadblocks or broken-down vehicles. The low accuracy of direction recognition in millimeter-wave radar and the reflection, insufficient light, and recognition distance issues in cameras contribute to poor recognition of static objects. To address this challenge, a solution involving broadcasting with the infrastructure Vehicle-to-Infrastructure (V2I) and cloud Vehicle-to-Everything (V2X) is proposed in this chapter.

(3) Poor perception capacity for road surface and environmental conditions

Environmental factors, such as road surface conditions, significantly affect L2 vehicle dynamics, including braking distance, which varies under different environmental conditions. When the sensor fails to perceive the current road conditions and the vehicle is controlled according to fixed parameters, it may cause control failure in emergency situations, leading to safety accidents, as shown in Figure 4.8. Ignoring the vehicle environment and controlling the vehicle according to fixed parameters cannot guarantee a safe following distance, particularly in wet or icy road conditions.

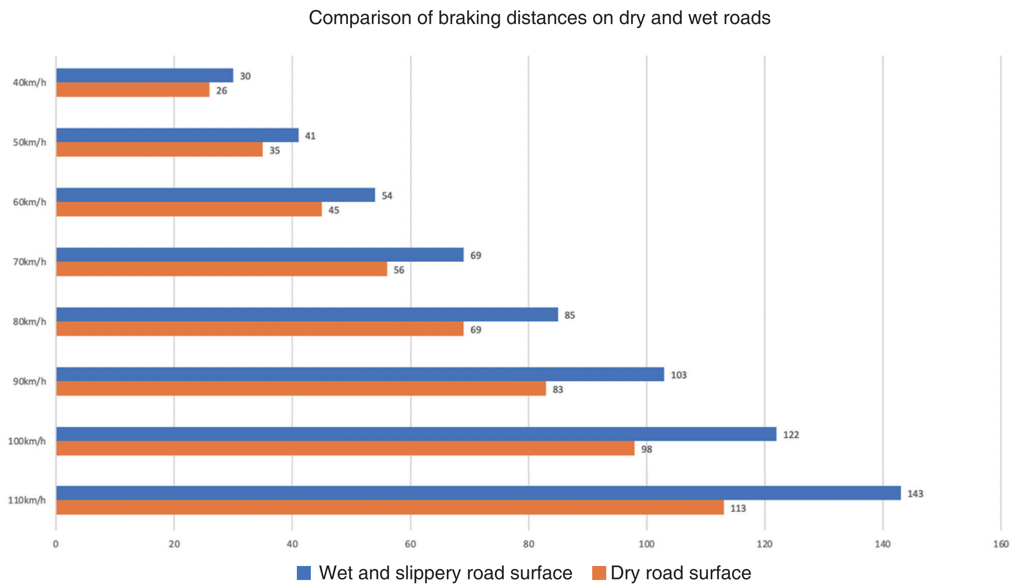


Figure 4.8 Comparison of Braking Distances on Dry and Wet Roads

Limited by the capabilities of vehicle sensors, L2 vehicles face challenges in obtaining comprehensive environmental information. However, through infrastructure perception and cloud information transmission, vehicles can overcome these limitations and obtain crucial environmental information, such as road conditions ahead. By doing so, L2 vehicles can ensure safe and efficient driving, despite limited sensor capabilities.

4.1.3.2 Restrictions on ODD: Urban and Parking Scenarios

In the realm of autonomous driving, the challenges faced by L2 autonomous vehicles are particularly pronounced with respect to their ODD. At present, the autonomous driving system is restricted to operating only in simple scenarios on expressways, while drivers are required to take over on urban roads and parking lots. In this context, it is important to examine the limitations on urban and parking lot scenarios, and the factors contributing to these limitations.

(I) Urban Scenario Restrictions on L2 Assistant Driving

L2 assistant driving still faces numerous technical and safety challenges when it comes to urban roads. Two notable scenarios that present significant challenges are traffic light recognition and HD map coverage and updating.

(1)Traffic Light Recognition Problem

The recognition of traffic lights is a primary challenge that L2 autonomous vehicles face on urban roads due to issues such as backlighting, multi-semantics, and occlusion. The current solution, which relies on traffic light recognition using a forward camera, struggles to systematically and thoroughly address all long-tail problems, making it difficult for L2 autonomous vehicles to cover urban road driving.

Figure 4.9 Traffic Light Recognition Problem

(2)HD Map Coverage and Update

Most L2 assistant driving solutions currently rely on HD maps, which provide crucial prior information to autonomous vehicles, enabling them to better navigate. However, HD maps face several challenges when it comes to extending L2 assistant driving to urban road scenarios, including:

1) Limited coverage of urban roads in HD maps, which are primarily designed for expressways and urban freeways, and are prohibitively expensive to construct.

2) Adequate renewal of HD maps, in order to reflect changes in the real world in a timely manner.

3) Dynamic layer update of the HD map, such as updating dynamic elements like road closures, variable lanes, and traffic restriction policies.

The lack of HD maps or inadequate renewal is also a key factor contributing to takeovers of L2 assistant driving, especially in situations where the vehicle is navigating in pilot driving mode. Consequently, there is an urgent need for a superior map change recognition, collection, and distribution solution within the industry.

(II) Restrictions on parking functions in public parking lots

Parking in a parking lot is a time-consuming and tedious activity that consumes a lot of a driver's energy in various driving scenarios. Autonomous driving technology can significantly improve the utilization rate of social resources and business efficiency and enhance the driving experience, particularly in public parking lots.
However, the current learning-based technology routes used for mass-produced autonomous parking solutions are only suitable for fixed scenarios, such as homes and

office areas. These solutions are based on vehicles' learning of driving behavior and the surrounding environment, and it is challenging to apply them to large public parking lots. Several restrictions limit the implementation of autonomous parking functions in public parking lots, including the loss of positioning capacity in occlusion environments and the lack of an industry standardization plan:

To provide automatic parking in parking lots, the vehicle needs to obtain parking space information from the parking lot management system and recognize the parking space assigned by the management system. The parking lot management system also needs to support parking space status management, reservation, allocation, parking guidance, automatic billing, and other essential functions. However, the current parking lot system is still in the stage where parking space occupancy and the number of available parking spaces indicators guide human drivers. It does not support essential functions such as parking space inquiry, reservation, allocation, parking guidance, and automatic billing, which are vital for standardizing autonomous driving services.

(1) Loss of positioning capacity in occlusion environment

The indoor positioning capabilities in multi-story parking lots, especially in complex scenarios, lack standard solutions, which limits the automatic parking function in parking lots. The current positioning methods, such as GNSS, RTK, and IMUs, used in autonomous driving, fail to eliminate the cumulative error over time of the IMU in case of indoor occlusion, due to the loss of reliable and standard absolute positioning signal sources. Therefore, the establishment and standardization of indoor positioning technology solutions are essential for the automatic parking of vehicles in parking lots.

(2) Lack of industry standardization plan

To provide automatic parking in parking lots, the vehicle needs to obtain parking space information from the parking lot management system and recognize the parking space assigned by the management system. The parking lot management system also needs to support parking space status management, reservation, allocation, parking guidance, automatic billing, and other essential functions. However, the current parking lot system is still in the stage where parking space occupancy and the number of available parking spaces indicators guide human drivers. It does not support essential functions such as parking space inquiry, reservation, allocation, parking guidance, and automatic billing, which are vital for standardizing autonomous driving services.
In the framework of vehicle-infrastructure collaboration, the management system of parking lots must be integrated into the comprehensive vehicle-infrastructure collaborative system, ensuring the standardization of interconnectivity among vehicles, infrastructure, and cloud services. This integration will enable a seamless and worry-free parking experience, leading to significant enhancements in both societal and commercial efficiency.

4.2
Services of L2 VICAD

4.2.1 Overall Technical Framework

VICAD is designed to improve the safety and driving experience of L2 autonomous vehicles through cooperative perception, assistant positioning, and part of cooperative decision-making and planning. The primary goal of VICAD is to enhance the perception and positioning of the L2 autonomous driving system, provide drivers with more decision-making information, and enable them to receive safety reminders from the infrastructure in a timely manner.

The overall service framework and logic of VICAD for L2 autonomous vehicles is depicted in Figure 4.10, and the main services that can be provided are presented in Table 4.1. VICAD's technical framework includes several components, such as the vehicle-to-infrastructure communication system, infrastructure sensing system, cloud platform, and intelligent algorithms.

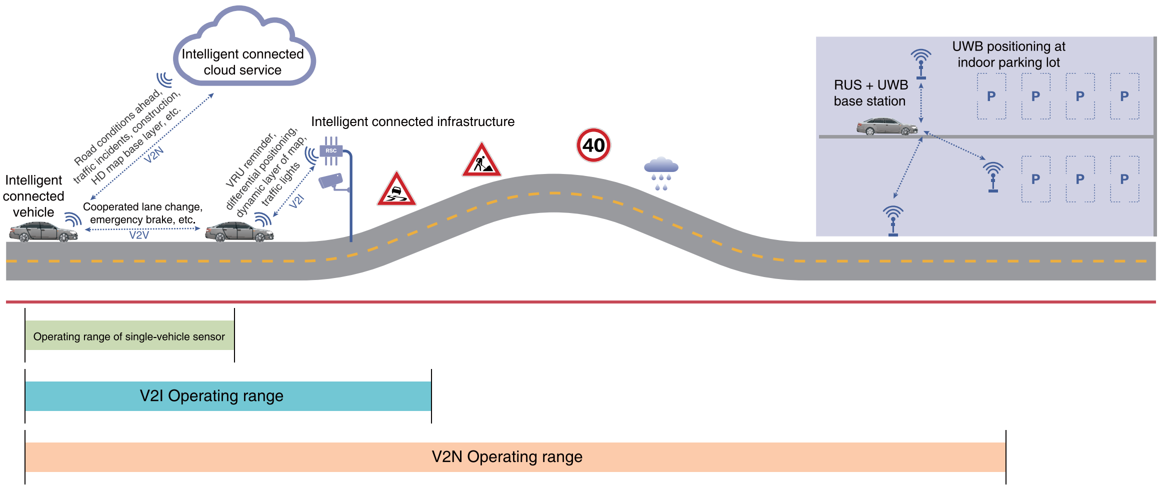


Figure 4.10 Overall Service Framework for L2 Based on VICAD

Service principal	Service contents	Real-time requirements
Cloud service	Analysis and output: a) Traffic accidents and road conditions information; b) Weather and other environment information; c) Construction, blocking and other information; d) HD map base-layer service; e) Aggregate and manage other services, such as parking lot guidance systems; f) Other traffic information; The mobile cellular Uu communication is used between the vehicle and the cloud. Specifically, the cloud receives the request from the vehicle and sends the corresponding information to the vehicle.	Event minute-level update Weekly or daily map update

Intelligent infrastructure	Incorporate infrastructure sensors, with vehicle V2X messages as inputs, and perform real-time data analysis, to output: a) Total perception results at infrastructure; b) Traffic light signal phase and countdown; c) Local dynamic layers of HD maps; d) Priority right-of-way signals; e) Safety reminder signals for pedestrians and non-motorized vehicle crossing and vehicle retrograde; f) Reminder signals for littering on the road surface and leftover objects; g) Provide vehicle cooperative traffic signals; h) Differential positioning reference signal, and indoor positioning reference signal; PC5, the standard communication mode, is adopted between the vehicle and the infrastructure, and C-V2X protocol standard is used.	Safety-related reminders: within 100 ms Other reminder signals: within 200 ms
Autonomous vehicle	a) Receive real-time information from the cloud and infrastructure; b) Integrate the input of the vehicle, infrastructure and cloud, to form a complete perception at the vehicle; c) Perform real-time interaction with the human driver, allowing the driver to predict the safety events ahead and prepare for the takeover if necessary.	

Table 4.1 Main Service Contents for L2 (Partial) Based on VICAD

4.2.2 Reference Technical Framework at Vehicle-Side

In the context of vehicle-infrastructure collaboration, the technical solution serving L2 requires consideration of not only vehicle-infrastructure cooperated autonomous driving, but also infrastructure events, cloud events, and real-time interaction with human drivers, as shown in Figure 4.11.

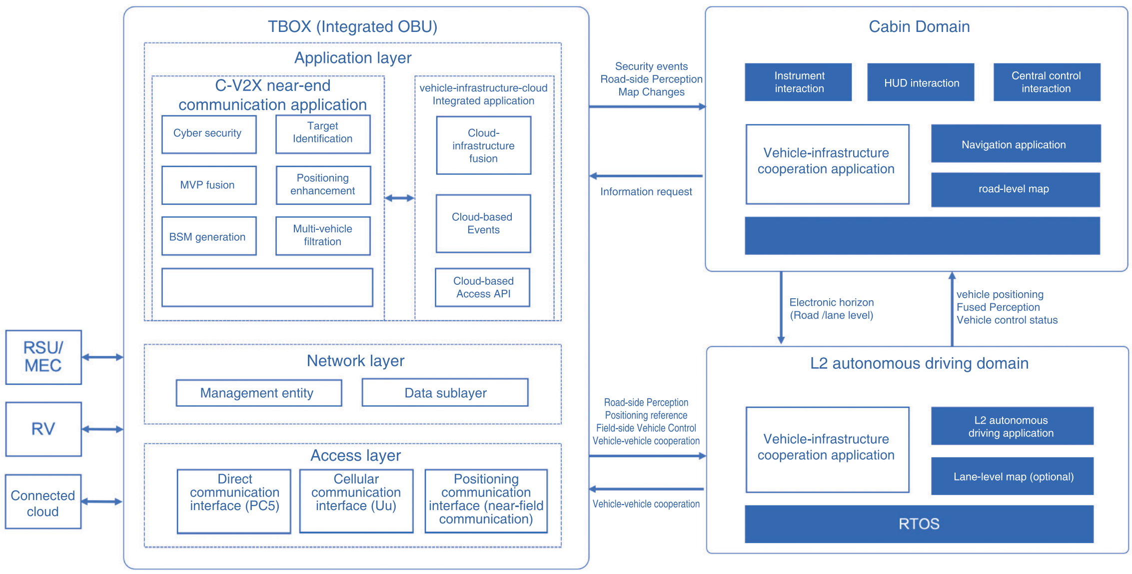


Figure 4.11 Reference Framework at Vehicle-Side

I n comparison to L4, the reference technical framework at the vehicle level for L2 autonomous vehicles involves three domain controllers, each with their respective function allocations:

1) T-BOX-OBU domain controller: It is primarily responsible for communication links with the cloud, infrastructure, and field-side. It processes V2X signals and outputs infrastructure perception, map changes, and safety events to the cockpit. It sends infrastructure perception, positioning reference signals, field-side vehicle control signals, and vehicle-vehicle coordination signals to the autonomous driving domain. Furthermore, it receives information requests from the cockpit domain controller and vehicle-vehicle cooperation messages from the autonomous driving domain controller.

2) Cockpit domain controller: It is designed for interaction with users, including the fusion of vehicle-infrastructure cooperation events and navigation applications. It displays information such as navigation and vehicle-infrastructure cooperation events to users through central control screens, HUDs, instruments, and other interfaces. This allows drivers to learn about the vehicle and environmental information output by the vehicle, infrastructure, and cloud. Additionally, the controller fuses infrastructure maps and local maps to generate map dynamic layer EHP information and sends it to the autonomous driving domain controller, allowing it to obtain the map ahead and dynamic layer information.

3) Autonomous driving domain controller: It is responsible for vehicle positioning, autonomous vehicle fusion and positioning, and receiving roadside positioning reference signals. It obtains post-fusion autonomous vehicle position, integrates infrastructure perception and autonomous vehicle perception to obtain complete environmental perception information, receives the vehicle control signal from the field-side, and completes the parking with the field-side vehicle control, particularly in scenarios such as the underground parking lot.

4.2.3 Vehicle-Infrastructure Cooperation Map Service and Update Solution

HD maps face challenges in map coverage and map updates. While map coverage can be continuously improved with the expansion of autonomous driving scenarios and market assembly rates, the update of HD maps will be a major challenge for autonomous driving, particularly at L2 level. HD map updates consist of two parts: identification of real-world changes and map updates. Industry solutions for change identification and updates include crowdsourcing, professional collection and update, and infrastructure map identification and update:

1) Crowdsourcing: It mainly relies on a large number of vehicles with environmental data collection capabilities.

2) Professional collection and update: It is costly and mainly used to ensure the first safe passage rather than real-time change identification

3) infrastructure map identification and update: It relies on smart infrastructure sensors such as cameras and radars to observe road changes in the coverage area, identify changes and update maps in real-time.

Compared to crowdsourced updates, infrastructure map update service offers several advantages.

1) High data freshness and stability: Infrastructure map update service provides high data freshness and stability due to its higher observation frequency of a fixed spatial range, resulting in a stable minute-level map update service. In contrast, crowdsourced updates require several revisits in the same lane within a certain period, depending on the frequency of changes in traffic elements in a specific spatial location, making the freshness of the crowdsourced map update random and unable to provide map update services for areas with low traffic flow.

2) Low cost: Infrastructure map update service is cost-effective because the main computing behavior is completed in the roadside computing unit, which does not require the transmission of the original sensor data through the 4G/5G network. In contrast, crowdsourced updates require the direct uploading of original or structured data to the cloud for aggregation. Since the aggregation platform requires a high number of revisits within a limited space, it incurs significant traffic charges.

3) High safety of first passage: Infrastructure map update service offers high safety of first passage as crowdsourced updates cannot solve the problem of map update when the vehicle passes by for the first time. Due to the high-frequency and continuous observation characteristics of roadside updates, the map change identification can be completed before the arrival of the vehicle using the map, ensuring safety related to maps.

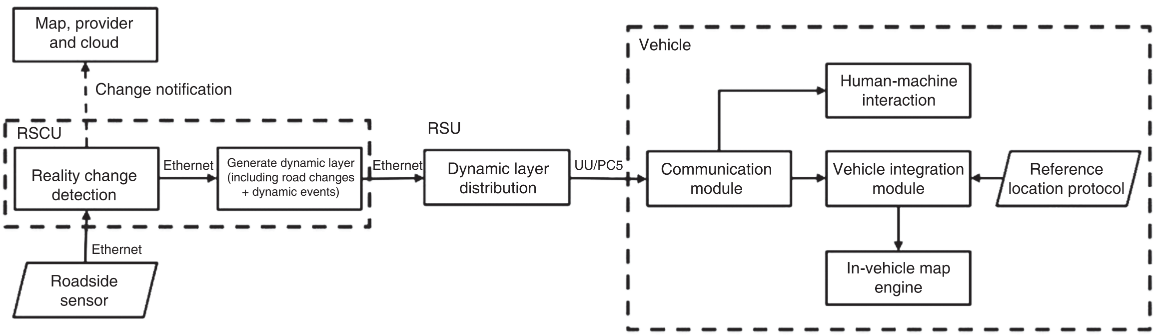


Figure 4.12 Map Update Architecture at Infrastructure

The process of updating roadside maps is depicted in Figure 4.12 and can be broken down into the following steps:

1) The roadside sensor transmits the original sensor data to the RSCU via Ethernet;

2) At fixed points, the RSCU detects map changes and dynamic traffic events, and generates local change information or map dynamic information based on the detection results. This information is then sent to the vehicle communication domain controller in the form of EHP using a high-speed communication protocol;

3) The vehicle's EHR analyzes the received map changes and dynamic traffic events, and sends them to the vehicle fusion module;

4) The vehicle fusion module integrates the received incremental map change information and dynamic events with the vehicle's HD map using the reference location protocol, making the updated map available for use by the autonomous driving system.

4.2.4 Vehicle-Infrastructure Cooperative Parking Services in Open Parking Lots

(1) System Definition and Classification

Vehicle-infrastructure cooperative parking systems build upon existing single-vehicle autonomous parking by incorporating cooperation between the vehicle and infrastructure. The parking area is divided into three levels to accommodate different vehicle configurations and field requirements.

1) The first level is Information Cooperative Parking. In this level, the field-side provides the vehicle with information about available parking spaces, reserves the parking spot, and offers positioning reference information without participating in route planning or vehicle control. The parking process can then be completed either by a human driver or automatically by a single vehicle using a vehicle map.

2) The second level is Planning Cooperative Parking. In addition to providing parking space information and reservation, the field-side also assists in driving route planning, and supports field-side perception compensation without directly controlling the vehicle.

3) The third level is Control Cooperative Parking. In this level, the field-side directly controls the vehicle, utilizing the field-side perception, vehicle positioning information, and single-vehicle perception information, which are sent to the field-side. The field-side then controls the vehicle to complete the parking process. This process requires the activation of the MEB function of the autonomous vehicle, and the field-side vehicle control state needs to be activated in case of emergency and then deactivated.

The three modes are compared below:

Cooperative parking mode	Vehicle route	Environment perception	Trajectory planning	Vehicle control
Information cooperative parking	Autonomous vehicle + field-side	Autonomous vehicle + field-side	Autonomous vehicle	Autonomous vehicle
Planning cooperative parking	Field-side	Autonomous vehicle + field-side	Autonomous vehicle	Autonomous vehicle
Control cooperative parking	Field-side	Field-side	Field-side	Field-side

Table 4.2 Three Cooperative Parking Modes

(2) System Architecture

The vehicle-infrastructure cooperative parking technology framework, illustrated in Figure 4.13, includes vehicle-infrastructure cooperative positioning, optional perception, route planning, and trajectory planning capabilities. The vehicle can select different levels of parking services at the field-side, depending on its configuration. The field-side must be upgraded to include vehicle-infrastructure communication, field-side positioning, parking lot map service, travel route planning, trajectory planning, vehicle control, and emergency manual takeover services.

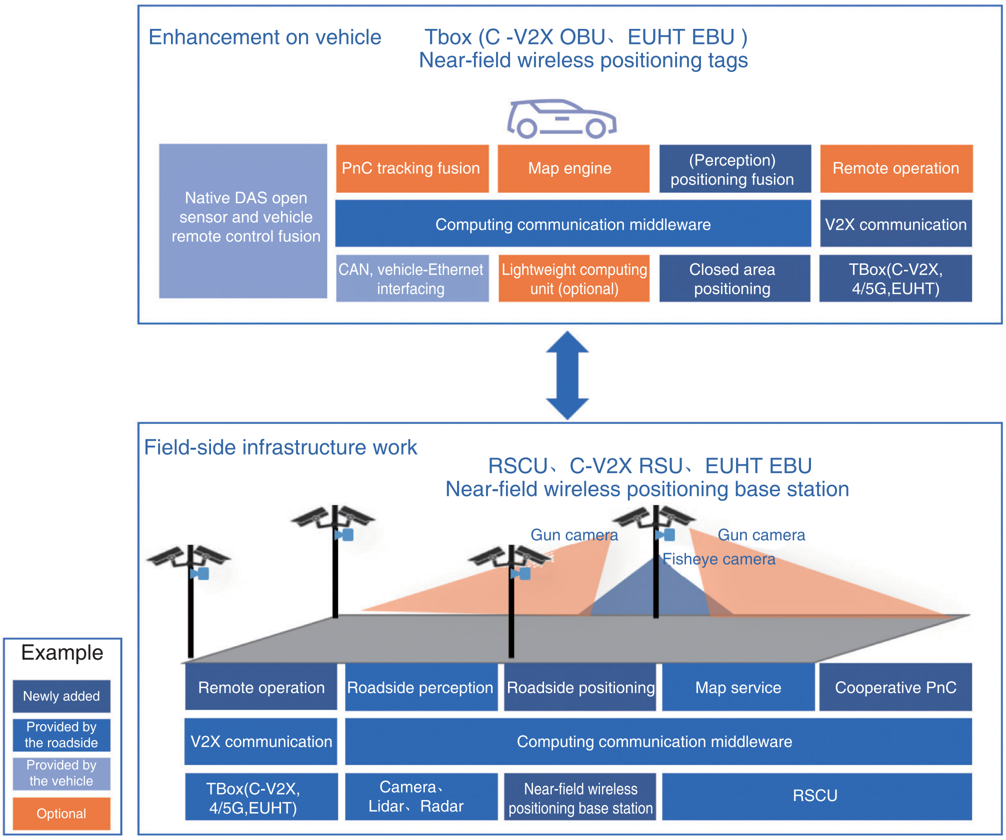


Figure 4.13 Architecture of Vehicle-infrastructure cooperative Parking System

(3) Cooperative Positioning

Positioning is a critical technical challenge for autonomous driving, especially in areas where satellite positioning signals are obstructed, such as tunnels, overpasses, and underground parking lots. To achieve high-accuracy positioning, assistant positioning facilities must be placed at the field-side or road-side.

Mainstream assistant positioning solutions include positioning identification, such as ArUco code, and near-field wireless positioning base stations, such as ultra-wideband (UWB) positioning technology, radio frequency identification positioning technology (RFID), Wi-Fi positioning system (Wi-Fi), visible light communication (VLC), and Bluetooth low energy (BLE) technologies. However, positioning identification has high maintenance difficulty and is highly coupled with the vehicle's software system. Therefore, near-field wireless positioning facilities at the field-side or road-side are considered more feasible to provide continuous and high-accuracy positioning information to complete parking guidance.

Figure 4.14 compares the mainstream near-field wireless positioning technologies. Options with higher accuracy, such as UWB and RFID, should be prioritized based on the technical requirements of autonomous driving and the vehicle-mounted electromechanical environment.

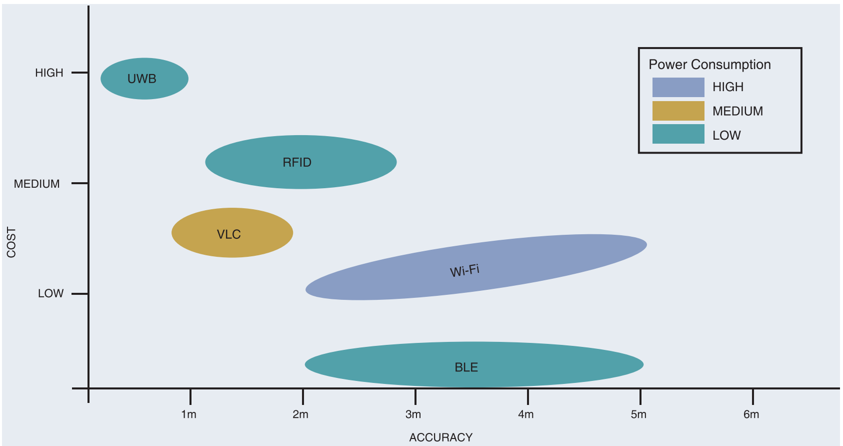


Figure 4.14 Comparison of Indoor Wireless Positioning Technologies

To ensure the continuity of positioning throughout the entire vehicle driving cycle, GNSS+RTK can be used to obtain global positioning signals in unblocked areas, while local near-field wireless positioning facilities can be used in obstructed areas to ensure the continuity of its spatial reference. Figure 4.15 illustrates how autonomous vehicles can ensure continuity of autonomous driving through continuous positioning and communication services.

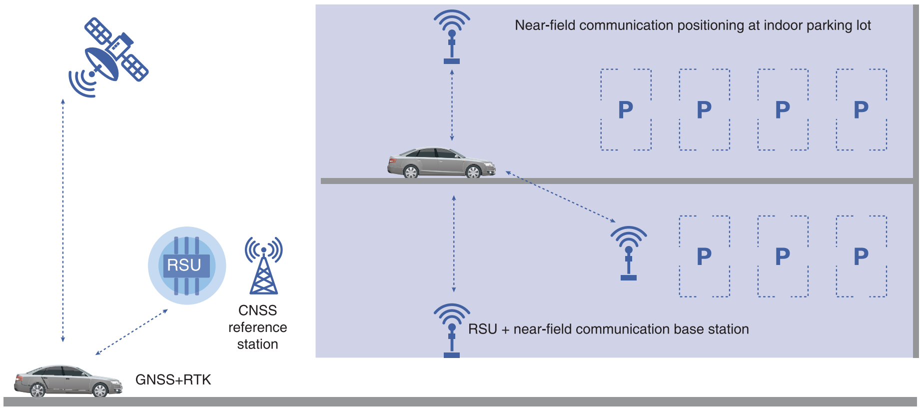


Figure 4.15 Indoor and Outdoor Roadside (Field) Assistant Positioning

(4) Parking process

There are three cooperative parking modes: information, planning, and control. Each mode utilizes field-side technology to identify vacant parking spaces and report real-time occupancy information to the roadside. Additionally, the operation management platform provides traffic management and map information, and conducts remote monitoring of the entire parking process. Emergency remote takeover services are also available for vehicles.

In the information cooperative parking mode, when a user or vehicle requests autonomous parking, the roadside allocates parking spaces based on real-time occupancy and the user's parking needs. The vehicle then uses the assistant positioning signal to perform autonomous vehicle positioning, while also generating its own driving trajectory and completing the parking process through vehicle control. Specifically:

1) The field-side is used to identify vacant parking spaces, covering all parking spaces in the lot, and reporting real-time occupancy information to the roadside.

2) If a user or vehicle requests autonomous parking, the roadside allocates parking spaces based on the user's needs and real-time occupancy.

3) After receiving the roadside route allocation information, the vehicle performs path planning according to the map.

4) The vehicle uses the assistant positioning signal at the field-side for autonomous vehicle positioning.

5) The vehicle uses its own sensors to perceive the environment, autonomously generates the driving trajectory, and completes the parking process through vehicle control.

6) The operation management platform provides traffic and map information in the parking lot, remotely monitors the entire parking process, and offers emergency takeover services for vehicles.

In the planning cooperative parking mode, the roadside also allocates parking spaces and performs global path planning based on real-time occupancy and user needs. The vehicle then parks according to the field-side positioning information, global path planning information, and map data. Perception results from the field-side are fused with the vehicle's own sensors to generate real-time driving trajectory. Specifically:

1) The field-side is used to identify vacant parking spaces, covering all parking spaces in the lot, and reporting real-time occupancy information to the roadside.

2) If a user or vehicle requests autonomous parking, the roadside allocates parking spaces and performs global path planning based on the user's needs and real-time occupancy.

3) After receiving the route allocation information, the vehicle parks according to the field-side positioning information, global path planning information, and map data.

4) After receiving perception results at the field-side, the vehicle performs fusion perception, generates real-time driving trajectory, and completes the parking process through vehicle control.

5) The operation management platform provides traffic and map information in the parking lot, remotely monitors the entire parking process, and offers emergency takeover services for vehicles.

In the control cooperative parking mode, the vehicle uploads its own perception and self-positioning data to the field-side, which fuses the data with field-side perception to generate the real-time driving trajectory. The field-side then sends a vehicle control signal to initiate parking, with the MEB function remaining enabled throughout the process. In case of a collision warning, parking should be stopped and the status should be reported to the field-side. Specifically:

1) The field-side is used to identify vacant parking spaces, covering all parking spaces in the lot, and reporting real-time occupancy information to the roadside.

2) If a user or vehicle requests autonomous parking, the roadside allocates parking spaces and performs global path planning based on the user's needs and real-time occupancy.

3) The vehicle uploads its own perception and self-positioning data to the field-side, which fuses the field-side perception to generate the real-time driving trajectory.

4) The field-side sends a vehicle control signal to the vehicle, which starts to park according to the signal.

5) The MEB function of the vehicle remains enabled throughout the process. During parking, if the collision warning is activated, the parking should be stopped, and the status should be reported to the field-side.

6) The operation management platform provides traffic and map information in the parking lot, global route and wheel path, remotely monitors the entire parking process, and offers emergency takeover services for vehicles.

(5) Application Benefits

The vehicle-infrastructure cooperative parking system enables vehicles to quickly locate available parking spaces, and automatically park and depart without the need for driver intervention. Users can simply drop off their vehicles at the parking lot entrance, and initiate the one-key parking program. The vehicle will then automatically park itself in the designated space. Upon departure, the vehicle will autonomously drive from the parking space and pick up the user, once the "one-key pick-up" function is enabled. The parking lot's management platform facilitates the centralized management of parking spaces and payments.

4.2.5 Vehicle-Infrastructure Cooperative Decision-Making and Planning

Currently, L2 autonomous driving faces various challenges, such as inadequate perception, poor coverage and updating of HD maps, weak positioning capability in blocked environments, and the lack of intention judgment and coordination with other vehicles. These issues are major causes of safety accidents and driver takeover. To address these challenges, vehicle-infrastructure cooperative decision planning uses VICAD methods for decision-making and planning based on vehicle-infrastructure cooperative perception, maps, and positioning. This approach extends the current L2 single-vehicle decision planning and integrates cooperative traffic methods, including vehicle-infrastructure cooperated lane change, vehicle-infrastructure cooperated ramp merging, vehicle-infrastructure cooperated intersection traffic, and other innovative applications.

(1) Vehicle-Infrastructure Cooperated Lane Change

The vehicle-infrastructure cooperated lane change scenario is as follows:

1) The HV is driving normally on the road, and the NV is driving in the adjacent lane.

2) HV and RSU have wireless communication capabilities, while NV does not.

3) RSU has perception and wireless communication capabilities.

4) HV needs to change lanes during driving. HV sends a lane change intention to the RSU, which transmits guidance information to HV based on the HV information and the current driving status of the vehicle in the target lane, as shown in Figure 4.16. This process ensures that HV can safely change lanes or delay the lane change

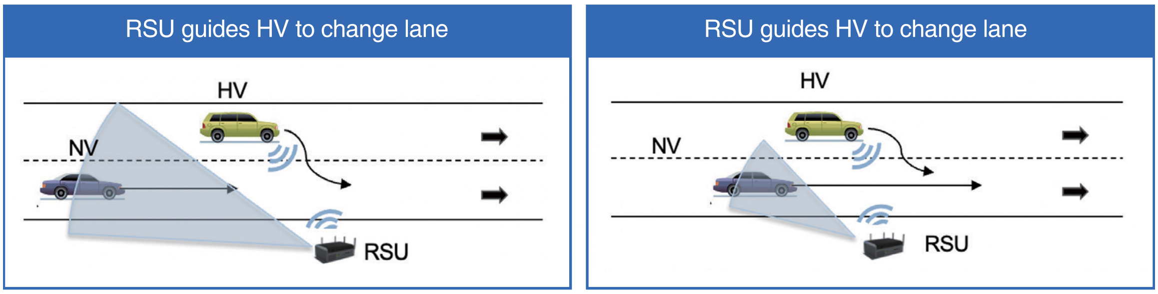


Figure 4.16 Vehicle-infrastructure Cooperated Lane Change

(3)Vehicle-Infrastructure Cooperated Ramp Merging

The process of vehicle-infrastructure cooperation in the merging of a ramp is described as follows:

1) The HV drives onto the ramp, preparing to merge onto the main road. At this point, a NV is driving straight in the rightmost lane of the main road, and an RSU is situated near the ramp, as illustrated in Figure 4.17.

2) The HV has wireless communication capabilities, while the NV may or may not support such capabilities.

3) The RSU is equipped with both perception and wireless communication capabilities.

4) Based on the driving state information of the ramp vehicle HV or the driving intention information transmitted by the HV, the RSU assesses that the HV is about to merge onto the main road. It then generates ramp merging guidance information based on the vehicle motion information on the main road and sends it to the ramp vehicle HV.

5) The HV receives the guidance information and generates a planned driving trajectory based on its own operating status and the information about other traffic participants on the main road. By doing so, the HV merges safely into the main road without affecting the vehicles already on the road.

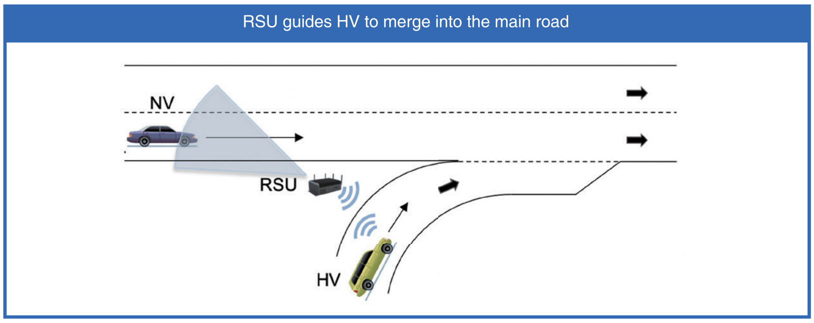


Figure 4.17 Vehicle-infrastructure Cooperated Ramp Merging

(4) Vehicle-infrastructure cooperated intersection traffic

Vehicle-infrastructure cooperation for intersection traffic relies on the integration of wireless communication capabilities in HVs and RSUs. This technology allows HVs to safely and efficiently navigate intersections without the need for traffic lights. This function is particularly useful in areas with surface roads and highways in cities, suburbs, and parks where traffic lights may not be present. To illustrate this concept, we can refer to Figure 4.18. The scenario of vehicle-infrastructure cooperation for intersection traffic involves three vehicles - HV-1, HV-2, and HV-3.

1) HV-1 is approaching the intersection and intends to turn left, while HV-2 is in the adjacent lane and driving straight. HV-3 is also approaching the intersection from the opposite direction, intending to drive straight.

2) The intersection is equipped with an RSU that supports wireless communication and perception capabilities.

3) HV-1 and HV-2 have wireless communication capabilities, while HV-3 does not.

4) HV-1 and HV-2 report their passage intentions to the RSU, which then synthesizes this information and combines it with observations made regarding HV-3's intentions. The RSU generates comprehensive passage guidance information and sends it to HV-1 and HV-2. This ensures coordinated and safe passage through the intersection.

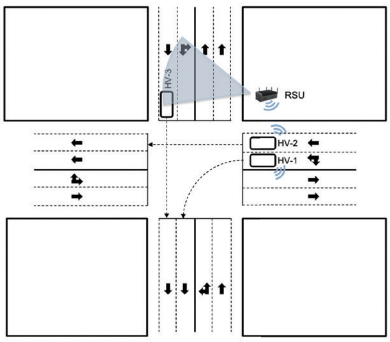


Figure 4.18 Vehicle-infrastructure Cooperated Intersection Traffic

4.2.6 Comprehensive Application Benefits

The vehicle-infrastructure cooperative L2 assistant driving based on the general framework of VICAD will greatly enhance the safety of vehicles. In the future, urban roads and indoor parking lots can be transformed into work areas, as shown in Figure 4.19.

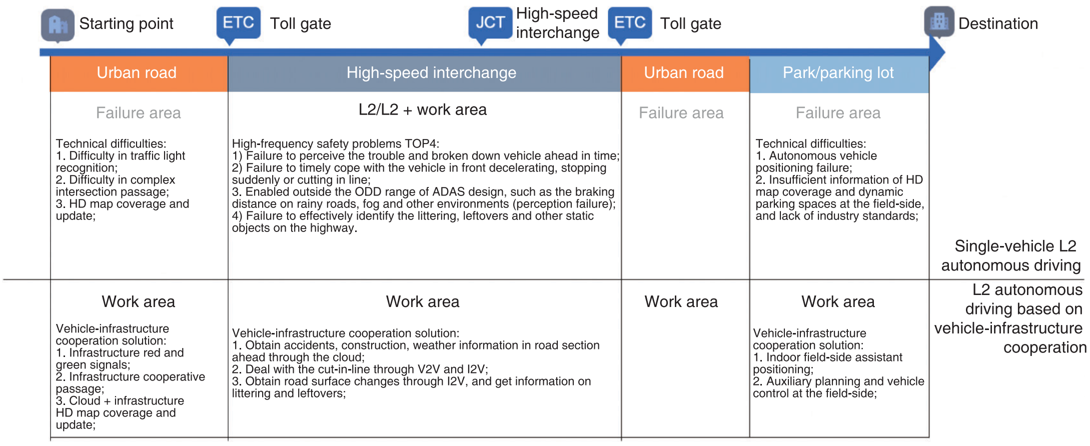


Figure 4.19 Comprehensive Application Benefits

4.3
Brief Summary

As previously mentioned, L2-level autonomous driving continues to face significant safety and scenario limitations. Safety issues arise frequently in high-speed scenarios, posing a threat to road users, while functionality is constrained in urban or obstructed scenarios, thereby impeding traffic flow efficiency and driving experience.

To address these limitations, the VICAD system has been developed to enhance L2-level autonomous driving safety, user experience, and social traffic safety and efficiency. VICAD aims to facilitate worry-free and hassle-free mass-produced autonomous driving by improving safety and effectiveness in L2-level autonomous driving, enhancing user experience, and optimizing social traffic safety and efficiency. Its implementation can lead to a significant improvement in the quality and reliability of autonomous driving technology, ultimately enabling it to become a viable transportation option for a wider population.

05

VICAD Needs Construction of High-level Intelligent Road

VICAD represents not only a technical proposition but also a grand industrial proposition. Viewed from a global perspective, numerous countries have attached great importance to the development of VICAD, raising it to the level of a national strategic priority. The principal reason for this focus on VICAD is not only that it can accelerate the promotion and application of autonomous driving, improving traffic safety and travel efficiency, but also because it represents a cross-industry project capable of driving the leapfrog upgrading of the automobile, communication, transportation, semiconductor, and other related industries. In so doing, VICAD can accelerate the construction of a transportation system characterized by automation and intelligence, thereby ushering in a new era of intelligent city and society.

The successful development of VICAD requires synchronous and collaborative development at the vehicle, infrastructure, and cloud levels. The core focus and top priority of VICAD development are to construct high-level intelligent roads that comprehensively improve the perception and cognition, connection and communication, map positioning, and decision control capacities of road infrastructure. To this end, China should leverage its own system and mechanism advantages, strategic policy advantages, and technology industry advantages to formulate a feasible and sustainable technology industry route for VICAD and lead the development of global autonomous driving and intelligent connected vehicles.

5.1
High-level Intelligent Road System Design

5.1.1 Intelligent Road Classification Standards

There are two primary motivations for implementing an intelligent hierarchical classification of roads:

Firstly, different levels of intelligent driving vehicles require varying degrees of support from the road infrastructure to achieve commercialization on a large scale. VICAD system has become a clear technological route for the development of higher-level autonomous driving in China, realizing commercialization on a large scale for different levels of autonomous driving vehicles requires varying levels of road capabilities. For example, for L2 and below autonomous vehicles where the driver remains responsible for driving and safety, roads primarily require perception capabilities. In contrast, to achieve commercialization on a large scale for L3-L5 autonomous vehicles, roads require a higher level of intelligent capabilities.

Secondly, China's vast network of expressways requires a hierarchical planning and construction approach to upgrade to an intelligent infrastructure. By the end of 2021, China's total highway length had reached 5.2807 million kilometers, including 169,100 kilometers of expressways[30] , ranking first in the world. To achieve the intelligent construction of such a massive highway system, a reasonable construction plan and technical roadmap are required. Given the different regional conditions and demand for intelligence across the highways, the development of intelligent roads in China should consider the varying functional needs of highways in different regions and classify highways into different levels of intelligence. A differentiated strategy for step-by-step construction can then be adopted.

The main reference for domestic and foreign autonomous driving and road classification standards includes:

1) SAE J3016-2021 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles;

2) SAE J3216-2021 Cooperative Driving Automation: Definitions and Taxonomy;

3) The Taxonomy of Driving Automation for Vehicles (GB/T 40429-2021);

4) ISAD issued by ERTAC[31] ;

5) The Definition and Interpretation Report on the Classification and Interpretation

30. Statistical Bulletin on the Development of the Transportation Industry in 2021.
31. The infrastructure support levels for automated driving (ISAD) was clearly proposed in the Connected Automated Driving Roadmap released by the European Road Transport Research Advisory Council (ERTAC) in March 2019.

of Intelligent Connected Road System issued by the Autonomous Driving Working Committee and the Autonomous Driving Standardization Working Committee of the China Highway & Transportation Society;

6) Smart Expressway Classification, the group standard of China Intelligent Transportation Systems Association;

7) Highway Intelligent Digital Technical Specification, the China highway engineering industry standard;

8) Intelligent Connected Vehicle Classification, research subject of IMT 2020, etc.

The contents of the reference survey include:

1) The construction of car networking pilot zones and demonstrations of vehicle-to-infrastructure applications in cities such as Tianjin, Wuxi, Changsha, Beijing, Shanghai, and Guangzhou in China;

2) The design, construction, and development of new technologies for smart highways in China, including the Hangzhou-Shaoxing-Ningbo, Hangzhou-Shaoxing-Taizhou, Beijing-Xiong'an, and Yan'an-Chongqing smart highway projects.

The key elements to consider in the grading of intelligent roadways include:

1) Perception ability: including the recognition of traffic participants, traffic operating status, traffic environment types, dynamic and static characteristics, etc.;

2) Mapping ability: such as navigation maps, high-precision maps;

3) Positioning ability: meter-level, decimeter-level, centimeter-level;

4) Network communication ability: including effective payload, delay (minutes, seconds, milliseconds), reliability, coverage range, etc.;

5) Decision-making and control ability: automatic driving decision-making and control, traffic facility and traffic operation decision-making and control;

6) Safety and protection ability: including data security, network security, V2X communication security, geographic information security, trusted node authentication, etc.

Based on the above, the proposed grading standard for intelligent roadways that meets the commercial development needs of the VICAD scale is shown in Table 5.1.

Road intelligence classification		Road capacity						Correspondence with the development stage of VICAD	Vehicle requirements for realizing L4 closed loop
		Ancillary road facilities	Map	Perceptual recognition and positioning capabilitie	Network communication capability	Road-side computing power TOPS	Functional safety and SOTIF system		
None	C0: None	None	None	None	None	None	None	None	None
Low-level intelligent road	C1: Low intelligence level	• Basic traffic safety facilities • Basic traffic management facilities	SD navigation map	None	• 3G and 4G cellular communication • DSRC and LTE-V2X direct communication	0 -10	None	None	• L5 • L4 in a limited environment
	C2: Primary intelligence	• All C1 facilities • Direct communication facilities	SD navigation map (lane level)	None	• 4G cellular communication • DSRC and LTE-V2X direct communication	10 -50		Stage 1: Information interaction and collaboration	
	C3: Partial intelligence	• All C2 facilities • Perception facilities (single sensor) • Auxiliary positioning facilities, computing facilities, etc		• Machine and non-human environment perception and recognition • Meter-level positioning	• 4G and 5G cellular communication • DSRC and LTE-V2X direct communication • 500 ms end-to-end, low latency	50 -100	Optional	Stage 2.1: Primary collaborative perception	
High-level intelligent road	C4: High intelligence level	• All C3 facilities • High-precision fusion and perception positioning facilities • High-accuracy auxiliary positioning facilities • MEC, regional cloud control platform	HD map (static + dynamic)	• Real-time perception of total traffic elements • Multi-feature accurate recognition • Decimeter-level positioning	• 5G Uu cellular communication • LTE-V2X, NR-V2X and 5G • 200 ms end-to-end, ultra-low latency	100 -300	Mandatory	Stage 2.2: Advanced collaborative perception; Stage 3.1: Conditional collaborative decision control;	• L5 • L4 • L3 • L2+ • Under some conditions, it can even support L2 and below vehicles with fine-grained drive-by-wire chassis and vehicle positioning capabilities
	C5: full intelligence	• Continuous deployment of all C4 facilities • Cross-domain collaborative MEC and cloud control platform		• Full spatial-temporal total perception • Centimeter-level positioning	• Supporting 5G, NR-V2X, 6G, etc. • 100 ms end-to-end, very-low latency	300+		Stage 3.2: Fully collaborative decision control	

Note:

1) The grading of autonomous driving meets the requirements of the national standard " Taxonomy of Driving Automation for Vehicles (Draft for Approval)" in China;
2) This white paper collectively refers to intelligent roads of grade C4 and C5 as high-level intelligent roads;
3) This white paper proposes the technical grading of intelligent roads from the perspective of supporting the commercialization of autonomous driving at scale, and the intelligentization of infrastructure construction, management, operation and maintenance, law enforcement, information guidance, and supervision and publicity can be supplemented and improved in subsequent reports;
4) This technical grading applies to urban roads, expressways, and grade 1-4 highways, and other roads can be implemented by reference;
5) In this table, L2+ refers to AVs that have been upgraded from L2 level to deploy higher-level vehicle-infrastructure collaboration and supporting fusion, decision-making planning, and control modules to achieve closed-loop VICAD.

Table 5.1 Grading of Road Intelligent Technologies Enabling Autonomous Driving

5.1.2 High-level Intelligent Functionality Requirements

(1) C4-level Intelligent Road Performance Indicators

Based on the requirements of L4 autonomous driving for collaborative perception, collaborative decision-making, and control, the technical grading description, typical features, and specific indicator requirements for C4-level intelligent roads are proposed as shown in tables 5.2 and 5.3.

Road Functionality Requirements		Specific indicators
Traffic Object Perception and Positioning	Type Identification (motor vehicles, non-motorized vehicles, pedestrians, obstacles, etc.)	Accuracy ≥ 95%
		Recall rate ≥ 95%
	Position accuracy	3 m (99%)
		0.5 m (mean value requirement)
	Speed Magnitude Accuracy	4.5 m/s (99%)
		1.5 m/s (mean value)
	Speed Direction Accuracy	10° (99%)
	End-to-End Latency for Roadside Object Perception (including Communication Latency)	≤200 ms (99%)
	Data Transmission Frequency	≥10hz
Traffic Incident Perception and Positioning	Incident Type Recognition	Accuracy ≥ 95%
		Recall rate ≥ 95%
	Positioning accuracy	3 m (99%)
	End-to-End Latency for Incident Perception (including Communication Latency	≤200 ms (99%)
	Data Transmission Frequency	≥10 Hz
Traffic Signal Detection and Recognition	Accuracy of Roadside Traffic Signal Color Perception	99.9999%
	Fault Traffic light Status Recognition Rate	99.9999%
	End-to-End Latency for Traffic Signal Data.	≤200 ms (99%)
	Traffic Signal Data Transmission Frequency	≥8 Hz
Real-Time Detection of map elements	Detection of Changes in Physical Location and Attributes of Traffic Equipment	Accuracy ≥ 99%
		Recall rate ≥ 99%
	Detection of Changes in Physical Location and Attributes of Road Markings	Accuracy ≥ 99%
		Recall rate ≥ 99%

Table 5.2 Core Indicator Requirements for C4 Technology Classification and Intelligent Roads

Traffic Object Prediction	Final deviation of predicted 3-s trajectory	<3.5 m
	Average deviation of predicted 3-s trajectory	<1.5 m

Traffic Scenario Understanding	Malfunctional vehicle	Recall > 99%
	Queuing	Recall > 99%
	Construction	Recall > 99%
	Accident	Recall > 99%
	Congestion	Recall > 95%
	Temporary docking	Recall > 95%

Table 5.3 Core Indicator Requirements for C4-level Intelligent Road Decision-Making and Planning

(2) Analysis of Computing Power Requirements for C4 Level Intelligent Roads

To obtain the computing power requirements for intelligent roads under the VICAD technology roadmap, it is necessary to first benchmark and analyze the current status and trends of on-board computing power development under the AD technology roadmap. As shown in Figure 5.1, the on-board computing power of autonomous driving vehicles has now crossed the threshold of 1000 TOPS. The highest on-board computing power for autonomous driving vehicles in mass production, such as NIO ET7, Zhi Ji L7, and Apollo R6T, has reached 1200 TOPS. Industry leader NVIDIA even plans to launch its Thor chip with over 2000 TOPS on its DRIVE platform for autonomous driving in 2024.

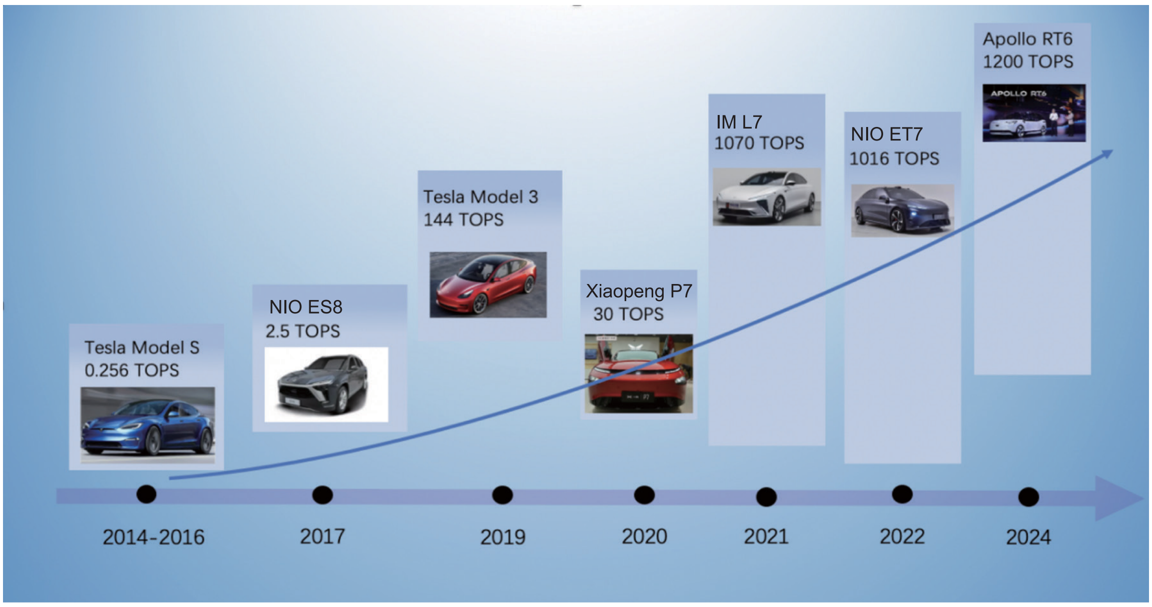


Figure 5.1 Development Trend of on-board Computing Power for Autonomous Vehicle

From the perspective of serving autonomous driving, as the development of roadside computing shifts from cooperative perception to cooperative decision-making and control, roadside computing and vehicle computing will show similar development trends. In addition, the computing power of a single roadside node will significantly exceed that of a single vehicle. The main reasons are as follows:

1) The specific tasks that need to be processed by the roadside and vehicle nodes in VICAD system are identical, including perception, mapping, positioning, decision-making, planning, and control, with high requirements for reliability, precision, and low latency. For example, in the perception process, target detection tasks need to deal with more than 20 types of participants and obstacles in four categories. In terms of accuracy, typical positioning accuracy needs to reach a decimeter-level accuracy with a 99th percentile constraint. In terms of real-time performance, the typical end-to-end latency (from the occurrence of a physical world event to the issuance of control) needs to reach a hundred milliseconds with a 99th percentile constraint. In terms of coordination, multiple sensors, traffic participants, and infrastructure need to achieve spatiotemporal calibration and ability coordination. In terms of safety, the system must be significantly better than human drivers, which means that the system's safety and redundancy, as well as protection mechanisms, need to be systematically designed to support an autonomous driving pass rate of over 99.9999% in various scenarios.

2) The roadside node not only needs to solve the problem of individual vehicle optimization but also has the responsibility and mission of group and global optimization, requiring higher computational power support. VICAD differs from single-vehicle intelligence and is a new form of intelligence. By introducing new intelligent elements, high-dimensional data can be obtained, and flexible computing power and algorithm mechanisms can be used to develop individual intelligence into cooperative intelligence or group intelligence, providing more diversified application services, such as intelligent traffic control, monitoring and law enforcement, and toll collection. For example, in terms of high-dimensional data, VICAD will produce a large amount of data, and the information characteristics have some orthogonal properties with single-vehicle intelligence data. After the fusion of vehicle-road coordination, new higher-dimensional data will be formed, such as spatial dimension (range, perspective, blind spot), time dimension (dynamic/static, time range), and type dimension (multi-source, multi-layer), which are distributed in different dimensions and have a larger amount of information on the orthogonal high-dimensional data. This will provide more effective assistance to the intelligent system. The comparison of VICAD and AD data dimensions is shown in Table 5.4.

Dimension category	Dimension subcategory	AD data dimension features	VICAD data dimension features
Spatial dimension	Scope	Limited to local range; with equivalent equipment, more precise observation can be achieved through denser deployment.	Multi-point global range, and beyond visual range; conditional deployment according to local conditions
	Visual angle	First-person view has advantages, but is easily affected by the range of visibility	Advantages of multiple angles, can provide a bird's-eye view perspective
	Blind spot	Centralized deployment of sensors on the vehicle easily lead to static blind spots and dynamic occlusion blind spots, which can be compensated by inferring the state of blind spots through motion reasoning	The observation is higher than that of the participants, so the blind spots are small and can be eliminated by overlapping multiple sensor areas.
Time dimension	Dynamic/ static	The observation point is dynamically moving, which makes observation difficult, but there are also advantages of verifying the dynamic perspective changes before and after; observing relative changes.	The observation point is static, allowing for long-term observation and differentiation of differences.
	Time limit	Single vehicle in real time	Continuous observation enables long-term reasoning and prediction of the future.
Type dimension	Multi-source multi-layer	Single-vehicle sensor, real-time and primary data	Multi-source and multi-layer data from traffic, scenes, users, and other sources can be used for high-level inference, such as disaster and anomaly detection. This includes cross-domain and cross-industry information such as traffic lights, weather, and cultural activities.
Other dimensional properties		The equipment deployed inside the vehicle according to the vehicle regulations shall be small in size, resistant to high temperature, vibration and electromagnetic, and with limited capacity.	Equipment, with larger volume and weight, can be equipped on the side of the road, and different types of shapes can be selected, with the high upper limit.

Table 5.4 Comparison of AD and VICAD Data Dimensions

Overall, for low-level roads currently, the deployed roadside devices have relatively simple functions, small amounts of data, and simple algorithm models. In order to achieve the performance indicators listed in Tables 5.2 and 5.3 for high-level intelligent roads, the increase in the number and types of sensors and the improvement in resolution have led to a huge demand for data processing, and the complexity of algorithm models has also significantly increased. Therefore, it is necessary to increase computational power and construct and deploy computing devices or facilities to perform critical tasks such as data aggregation, perception fusion, task scheduling, and data storage. Table 5.5 lists the recommended computational power requirements for different levels of intelligent roads based on the roadside computational power in several Vehicle Infrastructure Cooperative Autonomous Driving demonstration areas in China. At present, the computational power of a single roadside node for high-level autonomous driving applications should be no less than 100 TOPS.

Road intelligence level		C0-C1	C2	C3	C4-C5
perceptual recognition capabilities		Without or with weak perception capability	Traffic monitoring, traffic law enforcement	Compatible with C2 capability, traffic object detection, traffic operation status recognition, lane-level positioning	Compatible with C3 capability, traffic incident detection, total traffic object perception, high-accuracy positioning, traffic operation status recognition, etc.
end-to-end delay		Seconds-minutes	Second level	<500 ms	<200 ms
computing power at intersections		0-10 TOPS	10-50 TOPS	50-100 TOPS	100-300 TOPS
Automation application	L4 autonomous driving				√
	L3 Pilot aided driving				√
Connected application	Intelligent management of road infrastructure				√
	Security information real-time reminder			√	√
	Lane and vehicle behavior supervision			√	√
	Intelligent connected bus		√	√	√
Digital application	Smart parking		√	√	√
	Smart urban management and road management		√	√	√
	Smart traffic management		√	√	√
	In-vehicle infotainment	√	√	√	√
	Map navigation	√	√	√	√

Table 5.5 Computing Power Requirements for Intelligent Roads at Different Levels

(3) Sensor Performance Requirements of C4 Intelligent Road

The C4 intelligent road system is reliant on a variety of sensor equipment to collect information on all road elements. Perception sensors are required to operate continuously and in all weather conditions to manage various autonomous driving scenarios. Currently, mainstream perception sensor equipment includes visual sensors, lidar, and mmWave radar. Each type of sensor possesses a unique perception range, object recognition ability, and environmental adaptability. To achieve the best perception effect, it is essential to leverage the performance advantages of different sensors for equipment selection and program configuration.

	Camera	Millimeter-wave radar	Laser radar	Multi-sensor fusion
Object detection	Qualified	Excellent	Qualified	Excellent
Object classification	Excellent	Qualified	Poor	Excellent
Recognition range	Qualified	Qualified	Excellent	Excellent
Lane tracking	Excellent	Poor	Poor	Excellent
Severe weather resistance	Poor	Qualified	Excellent	Excellent
Low light environment	Qualified	Excellent	Excellent	Excellent

Excellent Qualified Poor

Figure 5.2 Comparison of Different Sensor Characteristics

(4) Map Requirements for C4 Intelligent Roads:

In the context of autonomous driving, maps serve a critical function:

1) As a virtual perception sensor that provides the autonomous driving system with highly reliable static traffic element structure and semantic information at long ranges, supplementing the on-board perception system effectively.

2) As a high-real-time, global spatial protocol that offers lane-level dynamic and static passage information for autonomous driving path planning, enabling autonomous vehicles to choose optimal time and space passing paths.

3) As a virtual, semantic traffic rule that provides clear behavioral constraint rules and geographic fences for autonomous driving decision-making and control modules, allowing autonomous vehicles to interact more safely with other traffic participants.

Items	Map requirements		
	Time resolution	Spatial resolution	Accuracy
Road conditions	1 min	Lane level	High
Road incident	Minute level	Lane level	High
Intersection incident	Minute level	Sub-meter level	Medium
Environment	Minute level	Lane level	High
Map element update	Minute level	Centimeter level	High

Table 5.6 Requirements of Maps for C4 Intelligent Road

5.1.3 Design of High-Level Intelligent Road

5.1.3.1 System Composition and Overall Architecture

The overall architecture of the high-level intelligent road system is shown in Figure 5.3. From a physical distribution perspective, it consists of three parts: vehicle end, roadside end, and cloud end.

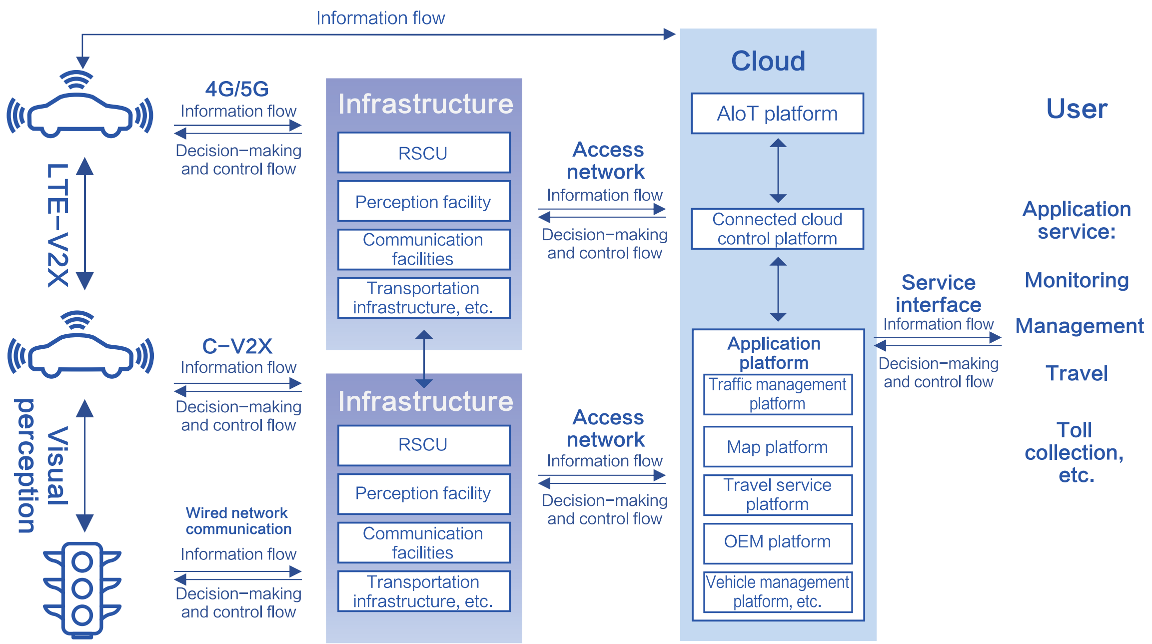


Figure 5.3 Overall Architecture of High-Level Intelligent Road System

(I) Reference Architecture for Vehicle End

Vehicles are an important component of the high-level intelligent road system and are both the service target and service provider. Vehicles should have both networked and intelligent capabilities, including:

1) Networked capabilities: vehicles should support PC5, Uu multimodal communication capabilities, and multi-terminal access methods. Vehicles should support multiple vehicle-to-road communication modes and communication protocols, including but not limited to 4G/5G based on Uu, and LTE-V2X, NR-V2X based on direct wireless communication. In terms of access methods, vehicle-mounted devices, front and rear T-Box, OBU, or other intelligent terminals can be used to support data sharing and diversified, personalized application services.

2) Intelligent capabilities: vehicles should support an intelligent driving system architecture with a hierarchical collaboration between vehicle, infrastructure, and cloud. As shown in Figure 5.4, the CAV vehicle intelligent driving system can not only analyze and process V2X message notifications, provide warning services to the driver through HMI or other means; but also further integrate with the perception, decision-making, planning, and control modules of the vehicle's intelligent driving system, to fully support safe and continuous autonomous driving.

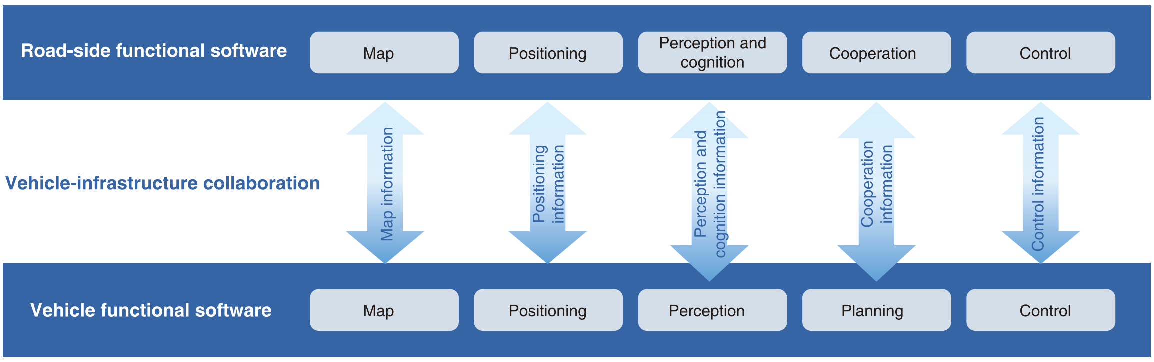


Figure 5.4 Open Compatibility of Vehicle Intelligent Driving System Architecture with Infrastructure

(II) Roadside Systems and Facilities

Roadside mainly includes various infrastructure and application service systems, where roadside systems include perception system, decision-making and planning system, signal control system, monitoring and enforcement system, toll system, etc. Roadside infrastructure includes perception facilities, Roadside Computing Unit (RSCU), communication facilities, traffic management facilities, traffic safety facilities, and various ancillary facilities.

RSCU is the brain of the roadside system, carrying core computing capabilities, and integrating multiple subsystems together to provide autonomous driving services. RSCU exists in two forms, one is an independent node device deployed on the roadside, and the other is deployed on the edge cloud platform (also known as MEC platform). At the current level of technology development, to meet the requirements of high-level autonomous driving applications, RSCU is mainly deployed in the form of node devices closer to sensor devices.

RSCU should meet a series of application requirements such as high intelligence, high performance, high reliability, and openness. Its architecture shows a trend towards OS development. Figure 5.5 proposes a recommended overall architecture of RSCU, consisting of real-time operating system kernel layer, hardware device abstraction layer, middleware layer, various domain services, vehicle-road-cloud communication, toolchain, and security modules.

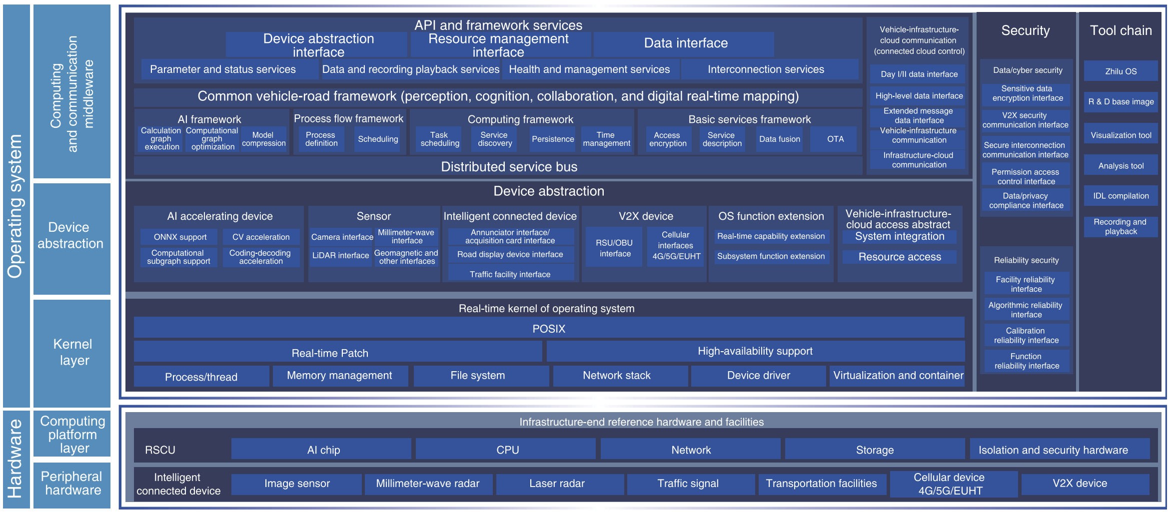


Figure 5.5 Roadside Computing Unit OS Reference Architecture

(1) Kernel layer: real-time operating system kernel layer provides necessary kernel-level support for the upper software stack and carries out customized optimization for real-time processing.

(2) Device abstraction layer: the device abstraction layer implements driver programs for various device facilities. It adapts to different manufacturers and different types of hardware devices.

(3) Middleware layer: the middleware layer includes general communication computing and AI acceleration computing middleware, etc. The communication middleware needs to meet requirements such as high concurrency, low latency, and high throughput. The AI acceleration computing middleware adapts to various AI chips and provides standard calling methods for AI algorithm programs.

(4) Domain services: to meet the requirements of vehicle-road cooperative autonomous driving, domain services should include low-latency traffic light services providing a unified traffic light interface, full obstacle perception services providing blind spot and beyond visual range capabilities for vehicles, intelligent collaboration services providing auxiliary decision-making and planning capabilities for vehicles, high-precision map services providing high-precision map engines, and parsing of high-precision map data, high-precision sensor equipment internal and external parameter calibration services, etc.

(5) Vehicle-infrastructure-cloud communication: provides vehicle-infrastructure and infrastructure-cloud communication capabilities, realizes seamless communication between vehicle, infrastructure, and cloud, and supports integrated computation and cooperation among vehicle, infrastructure, and cloud.

(6) Toolchain: the toolchain provides tool support for upper software compilation, debugging, and analysis.

(7) Security: provides security services from the underlying hardware to the operating system, device abstraction layer, middleware layer, service layer, and application layer.

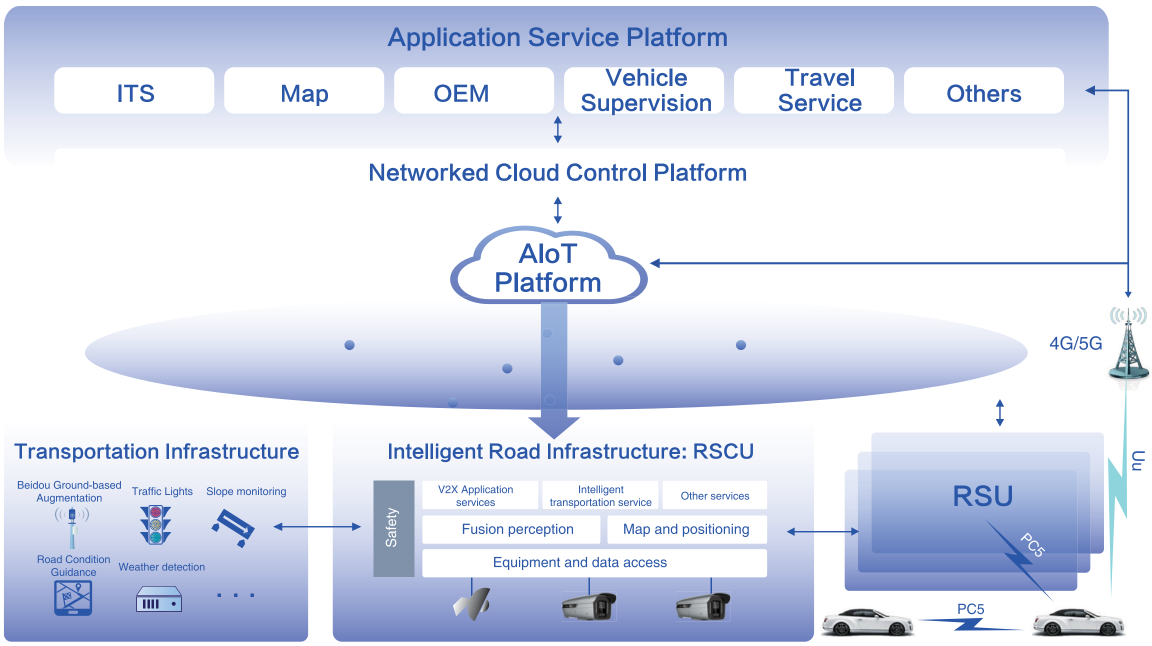


Figure 5.6 Main Components of High-level Intelligent Road

(III) Cloud platform

Figure 5.6 shows the main components of the high-level intelligent road. The cloud platform consists of three parts: the AIoT platform, the networked cloud control platform, and the application service platform.

(1) AIoT platform

The AIoT platform is based on device management, supported by cloud-edge-end AI computing, and aimed at data empowerment. It should have three key capabilities:

1) Connectivity based on traditional IoT platforms. The IoT platform connects various types of devices in the intelligent road system, providing basic services such as device management, operation and maintenance monitoring, and OTA.

2) AI computing capabilities. The platform provides edge computing fusion capabilities for device edges, LAN edges, and network edges, supporting flexible and elastic scheduling of cloud-edge-end computing resources. It collaboratively implements perception, planning, and decision-making for vehicle-infrastructure cooperation services and supports service scenarios with different delays, accuracies, and scales;

3) Data empowerment. Through massive data access capabilities, the platform aggregates, transforms, calculates, models, and analyzes vehicle-infrastructure-cloud data, provides data open services to the outside, and provides basic data support for the networked cloud control platform.

(2) Networked Cloud Control Platform

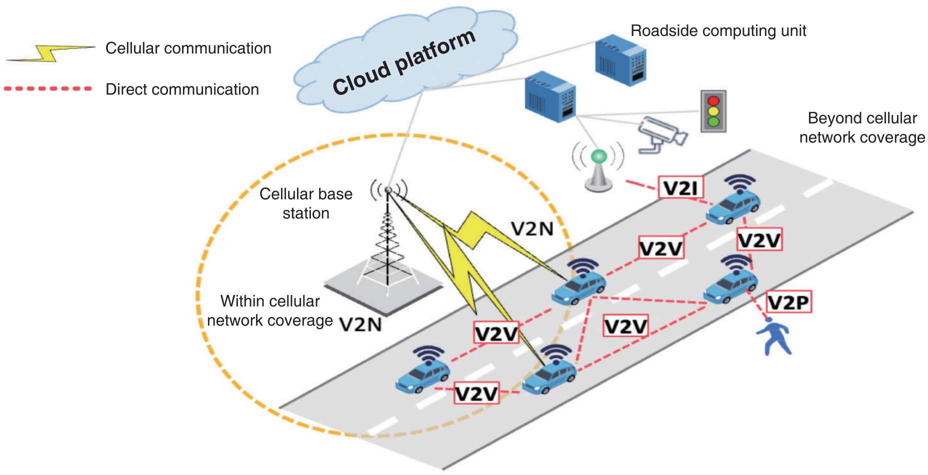
The networked cloud control platform is a platform system serving the vehicle infrastructure cooperation business. It has service capabilities such as real-time information fusion and sharing, intelligent application orchestration, and information security, and provides collaborative applications and data services such as assisted driving decision-making, transportation safety, and traffic management for intelligent vehicles, management agencies, and end users.

(3) Application Service Platform

The application service platform is supported by the networked cloud control platform and provides various differentiated and customized application services for the industry, such as passenger car networking services, traffic management, maps, travel, and supervision. From different perspectives such as road regulation, vehicle operation, and traffic governance, it provides professional solutions that follow the industry's business logic.

5.1.3.2 High-Reliability Communication Design

As a dedicated wireless communication technology for connected vehicles, C-V2X can provide low latency, high reliability, high speed, and secure communication capabilities in high-speed mobile environments, meeting the needs of various applications in the connected vehicle domain. C-V2X communication has two independent and complementary working modes: the PC5-based direct wireless communication mode and the Uu-based cellular mobile communication mode, which respectively satisfy the communication needs between different traffic elements. The PC5 direct communication mode addresses the short-range information exchange needs, while the Uu cellular mobile communication mode addresses the long-distance information service needs. The two communication modes complement each other and effectively ensure the continuity and reliability of connected vehicle services. Its system architecture design adopts a fusion of direct communication and cellular communication. C-V2X includes LTE-V2X based on LTE technology and 5G radio NR-V2X technology, both of which use the system architecture shown in Figure 5.7.



Note: This figure is adapted from "The Roadmap for the Industry and Technology Development of the Internet of Vehicles", provided by CICT Zhilian Technology Co., Ltd.

Figure 5.7 C-V2X Communication System Architecture for Fusion of Direct Wireless Communication and Cellular Mobile Communication

(1) Direct wireless communication

The direct communication mode is introduced to meet the low-latency and high-reliability requirements of V2X communication between vehicles, between vehicles and road infrastructure, and between vehicles and pedestrians. End-to-end data transmission between terminals can be achieved without passing through base stations, ensuring low-latency communication and meeting the requirement for fast information exchange between devices beyond cellular coverage. According to the definition in YD/T3400-2018, LTE-V2X direct communication for connected vehicles based on LTE technology meets the following functional requirements:

1) Connected vehicle terminals should be able to send and receive messages through direct communication. Roadside units should be able to send messages to connected vehicle terminals and receive messages from them. Connected vehicle terminals can also communicate with each other through the PC5 direct communication interface. The system should support efficient distribution of information to a large number of connected vehicle terminals and support high-density communication between them. The wireless signals used in this communication can also assist in supporting location-based services, achieving efficient reuse of air interface resources;

2) In terms of mobility, the system should support the highest relative speed of 500 km/h for sending messages between vehicles, and the absolute speed of 250 km/h for sending messages between vehicles and roadside units or pedestrians;

3) In terms of communication latency, for terminals supporting V2V and V2P communication, the maximum communication latency for direct or roadside unit-assisted transmission should not exceed 100ms. For special cases such as collision awareness, the maximum latency for V2V message transmission between connected vehicle terminals should not exceed 20ms. For communication between vehicles and roadside units, the maximum communication latency should not exceed 100ms.

4) In terms of message transmission frequency, the system should support message transmission frequencies of no less than 10 Hz between roadside units and connected vehicle terminals.

5) In terms of message size, excluding security-related message units, for periodic messages, the message size is 50-300 bytes; for event-triggered messages, the maximum message size is 1200 bytes.

The functional requirements related to 5G radio NR-V2X technology are defined in 3GPP TS23.287, and the formulation of relevant domestic industry standards is currently underway.

(II) Cellular Mobile Communication

The advancement of applications such as autonomous driving has placed higher demands on networks. High-level intelligent driving applications, such as vehicle platooning, semi-automated/automated driving, and remote driving, as defined by 3GPP TS22.186, require the adoption of an "integrated communication and computation" approach to construct a new mobile cellular network. This approach can meet the requirements for high reliability, large bandwidth, and further improve the service capabilities of the vehicle-to-cloud integration. The 5G Uu network has introduced new features such as V2X communication slicing, edge computing, and quality of service (QoS) prediction to achieve this goal.

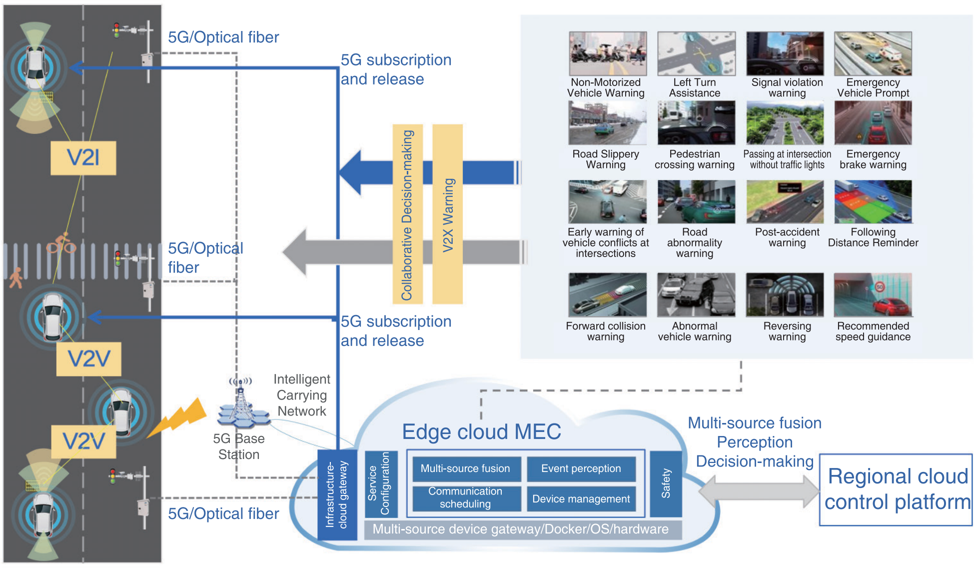
5G network slicing has typical characteristics such as "network function on-demand customization, automation, and business security isolation". By utilizing 5G public network resources and implementing end-to-end QoS or slicing technology, independent slices can be provided for V2I cooperative data transmission, ensuring low latency and guaranteed bandwidth, while also isolating other business data. Autonomous driving vehicles can access the edge cloud deployed at the mobile cellular network base station side through a 5G dedicated slicing channel. Meanwhile, the roadside perception system can also transmit data back to the edge cloud via 5G Uu or wired networks. The edge cloud achieves efficient interconnection with cloud control platforms through cloud-edge collaboration mechanisms and provides integrated processing of vehicle-to-cloud data, enabling different traffic event recognition and driver assistance warning information to be pushed to the vehicle side. Additionally, the 5G cellular network can enhance intelligent perception network communication performance and channel modeling under different scenarios. It can combine different QoS requirements of different businesses, perform pre-judgment of network quality, and provide timely warnings and channel optimization for business effectiveness.

The MEC edge computing device can batch process data from RSUs and OBUs with cameras, radar, traffic lights, etc. at multiple intersections. By fusing perception AI algorithms, it improves data processing efficiency and fusion degree, and the elastic expansion and intelligent scheduling characteristics of the MEC enable online expansion. It supports single intersection, multi-intersection, and regional collaborative applications, and can track, record, and analyze targets throughout the entire domain, supporting autonomous driving strategy formulation in complex scenarios, as well as cross-time and space driving path guidance. The MEC node adopts a standardized interoperable framework that supports on-demand subscription and real-time updates of application services in different domains, with the characteristic of "one-point distribution and full-network deployment". This enables the rapid promotion of standardized application services such as autonomous driving assistance, high-precision map distribution, and smart traffic control.

(III) Integration of Uu and PC5 for vehicular networks

As shown in Figure 5.8, for vehicle access, the integration of 5G Uu and PC5 direct communication networking is used. This approach leverages the large bandwidth and wide coverage of 5G for vehicle connectivity, supporting remote information services such as traffic navigation, map downloading, and vehicle dispatch, as well as regional cooperative information services such as HD map distribution and intelligent traffic management. At the same time, PC5 communication through RSUs is utilized to achieve coverage in critical scenarios such as intersections and hazardous road sections, enabling real-time near-field information interaction, ensuring timely and accurate delivery of roadside information to vehicles, and improving driving safety.

With the gradual large-scale deployment of 5G networks and effective improvements in key performance indicators, it has become an effective means of supporting business such as vehicle-infrastructure cooperation, remote driving, and cloud control services. The deployment of information infrastructure such as "cloud-network integration, computation-network integration, and cloud-edge collaboration" has further accelerated the commercial process of city-scale deployment of autonomous driving. Based on the foundation of 5G full-scenario connectivity, 6G will further achieve ubiquitous connectivity and establish a multi-level, seamless connection. As a key field of integration and convergence among multiple industries such as communication, transportation, and automotive, 6G will continue to enhance new features such as seamless switching, cooperative computing, trustworthy security, high-precision positioning, sensory fusion, and airspace integration, truly achieving autonomous driving in full-scenario environments.



Note: This solution is provided by China Unicom Smart Connection Technology Co., Ltd.

Figure 5.8 5G Vehicle-infrastructure Collaborative Service Network Based on Computation-Network Integration

5.1.3.3 System high-availability design

VICAD system sets higher requirements for system reliability, and the Intelligent Transport System (ITS) plays a crucial role as a fundamental infrastructure in VICAD. The ITS system itself is a complex system that comprises vehicles, infrastructure, and clouds, with complex road environments, long communication links, and high-performance requirements. Therefore, the design of a highly available system is particularly important. The factors that need to be considered in the design of a highly available ITS system include, but are not limited to:

1) High availability of road equipment and facilities, particularly in response to various weather conditions.

2) High availability of communication systems, which are an important part of the VICAD application and must ensure sustainable and high-performance communication services.

3) High availability of computing and application services, which must meet the continuous high-quality service level requirements of the vehicle regulation level, particularly those related to collaborative decision-making and control services.

To meet these requirements, a highly available ITS system design can be focused on the following areas:

1) Redundancy backup of computing power: The system should have a certain redundancy design, and edge computing power should have clear indicators for measuring pressure. When the system capacity reaches the limit, which affects the system performance indicators, elastic scheduling can be achieved through redundant computing power.

2) Load balancing: Application services should have load balancing capabilities. For example, for vehicle-cloud communication, the cloud should have the ability to distribute traffic evenly to different application service instances to enhance service throughput.

3) Multi-level recovery: The system should have the ability to recover from single-room, single-machine, or single-instance failures without external intervention, ensuring that services can be switched without a single point of failure.

4) Hierarchical degradation: Service design should meet the minimum function principle, fully considering the dependency between different components, reducing the tight coupling of functional services. Services can be divided into core services and non-core services, and non-core service exceptions can be quickly removed to ensure the availability of core functions, with service degradation capabilities.

5) Network isolation: The system should have a network security control strategy to detect and prevent network sniffing, DDoS attacks (distributed denial-of-service attacks), etc., reduce machine attack surfaces, and reduce the risk of being attacked.

6) Gray release and rollback mechanism: The vehicle-infrastructure-cloud development environment should have gray-scale release capabilities. After small-scale testing and verification, if there are problems, there should be a rollback mechanism to quickly restore the stable version before the gray-scale release.

7) Monitoring and alerting: The ITS system construction environment is complex, with long links, and multiple hardware devices. Real-time monitoring of roadside infrastructure, network, system resources, device status, software operation status, and vehicle hardware and software status can improve operational efficiency by detecting and locating problems in a timely manner.

5.1.3.4 Security Design and Security Management

The intelligent road system's security design should include three parts: basic system security, operational security, and data security. Basic system security refers to infrastructure security, including host security, communication security, etc. Operational security refers to security protection measures such as identity authentication, access control, and security auditing to ensure the reliability, effectiveness, and auditability of the system during remote operation by operators. Data security refers to data security protection in data acquisition, transmission, storage, sharing, and other links.

Among them, communication security is an important component of vehicle-road collaborative automated driving safety, including network communication security and C-V2X communication security. As shown in Figure 5.9, digital identities (V2X certificates) should be issued to communication terminals, secure messages should be constructed based on identities to ensure the authenticity and credibility of PC5 messages, and pseudonym certificates should be used to protect the location privacy of vehicles.

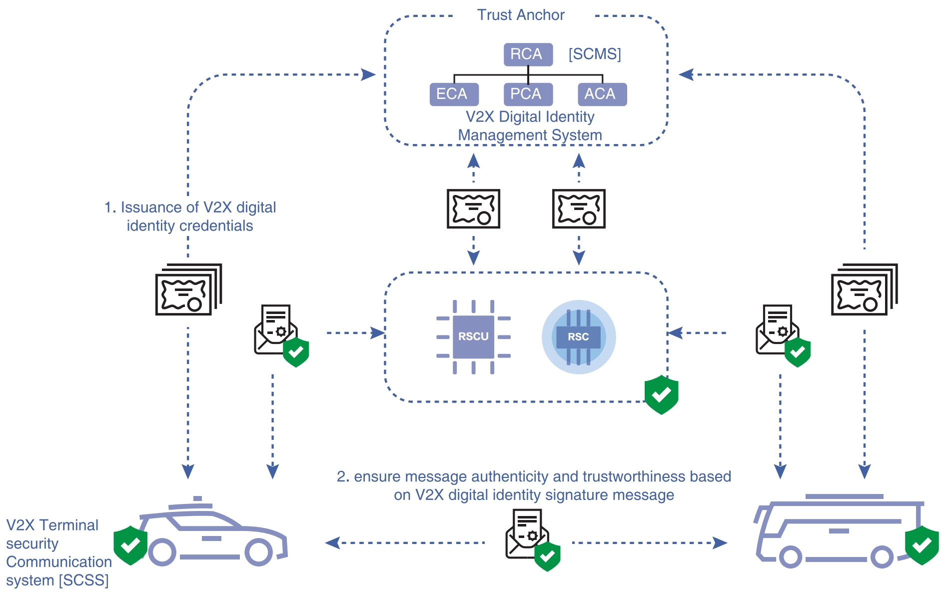


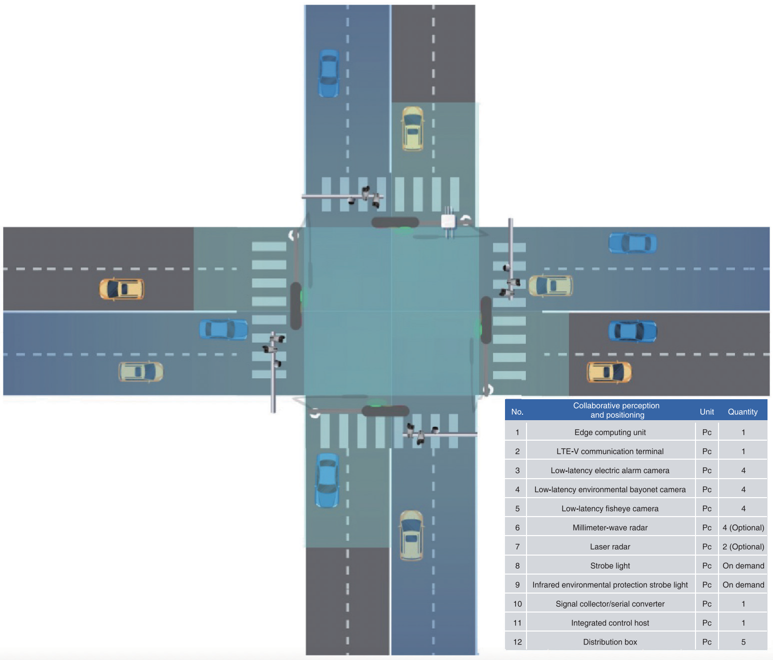
Figure 5.9 C-V2X Communication Security

5.1.3.5 Construction and Deployment Strategy

Taking standard intersections and standard road sections as examples, the specific construction and deployment plan of C4 high-level intelligent roads is introduced below.

(1) C4 Standard Intersection Deployment

To equip the intersection with intelligent capabilities, four monitoring poles and one signal pole are selected for installation of perception, RSCUs, communication equipment, and corresponding accessories in each of the four directions. Furthermore, the power and network infrastructure are established as a separate local network. The deployment schematic and main equipment list are illustrated in Figure 5.10.



No.	Collaborative perception and positioning	Unit	Quantity
1	Edge computing unit	Pc	1
2	LTE-V communication terminal	Pc	1
3	Low-latency electric alarm camera	Pc	4
4	Low-latency environmental bayonet camera	Pc	4
5	Low-latency fisheye camera	Pc	4
6	Millimeter-wave radar	Pc	4 (Optional)
7	Laser radar	Pc	2 (Optional)
8	Strobe light	Pc	On demand
9	Infrared environmental protection strobe light	Pc	On demand
10	Signal collector/serial converter	Pc	1
11	Integrated control host	Pc	1
12	Distribution box	Pc	5

Figure 5.10 Perception Coverage and Deployment Schematic for a Standard Intersection.

(2) C4 Standard Road Section Deployment

For the deployment of C4 capabilities along a road section, two monitoring poles in two directions are selected for installation of perception, roadside computing units, communication equipment, and corresponding accessories. The power and network infrastructure are also established as a separate local area network. The deployment schematic and main equipment list are shown in Figure 5.11.

No.	Collaborative perception and positioning	Unit	Quantity	No.	Collaborative perception and positioning	Unit	Quantity
1	Edge computing unit	Pc	1	7	Laser radar	Pc	2 (Optional)
2	LTE-V communication terminal	Pc	1	8	Strobe light	Pc	On demand
3	Low-latency electric alarm camera	Pc	2	9	Infrared environmental protection strobe light	Pc	On demand
4	Low-latency environmental bayonet camera	Pc	2	10	Signal collector/serial converter	Pc	1
5	Low-latency fisheye camera	Pc	2	11	Integrated control host	Pc	1
6	Millimeter-wave radar	Pc	2 (Optional)	12	Distribution box	Pc	2

Figure 5.11 Perception Coverage and Deployment Schematic for a standard road section

The solution possesses the following salient features and advantages:

1) Primarily Visual Perception

The perception devices for intersections and road segments mainly employ pure visual perception cameras. Only a few lidar devices are selected for complex or special road environments, greatly reducing the number and complexity of road equipment and facilities, while ensuring equivalent perception accuracy and positioning capabilities. As a result, the construction cost is significantly reduced.

2) Comprehensive Coverage and High-Precision Perception and Positioning

This solution can achieve comprehensive coverage of road environments such as main road lanes, auxiliary road lanes, non-motorized vehicle lanes, and right-turn lanes. In terms of perception capabilities, through the fusion of multiple perspectives, it can achieve accurate identification and positioning of all traffic participants and traffic events and meet the demand for L4 high-level autonomous driving.

3) Smooth Upgradability at Roadside

The roadside solution supports smooth upgradability. By adding terminal devices such as AI cameras and AI radars without changing the RSCU computing power configuration, it can meet the requirements for flexible expansion and multi-service integration and upgrading of constantly changing roadside environments, minimizing the upgrade and transformation costs of the roadside solution and achieving a smooth upgrade. Additionally, RSCU and related equipment facilities can also be upgraded online to continuously improve the capability and services of the roadside system.

4) Continuous Online Calibration to Improve Perception Robustness

Due to external factors, cameras may experience displacement, calibration parameter failure, and decreased perception accuracy. The traditional method requires calibration personnel to re-calibrate the camera's parameters, which incurs high labor costs and poor timeliness. Through online calibration algorithms, when a significant camera offset is detected, the system automatically performs online calibration, continuously ensuring the correctness of the roadside perception camera's calibration parameters, improving the robustness of the perception system and providing high-quality services for autonomous vehicles continuously.

5) Multi-Sensing, Multi-Pole and Multi-Box Integration

Multi-sensing integration refers to the integration of multiple sensing devices or multiple sensing functions into one set of sensing equipment to solve multiple business application problems. Roadside perception equipment is reused with traffic perception equipment (such as electronic police checkpoints) to achieve deep integration of multiple businesses such as networked vehicles and traffic management, avoiding duplicate investment in construction. This not only meets the demand for vehicle-road cooperation and autonomous driving but also possesses object-level, low-latency, high-precision, and high-reliability 3D full-object perception capabilities while meeting traffic management needs. It also realizes the illegal capture functions of traffic police electronic police and checkpoints, as well as the integrated management and control of electronic police checkpoints, reducing the number of road devices, beautifying the urban space, and facilitating centralized management and maintenance of equipment cabins.

Additionally, multi-pole integration reduces the occupancy of road space by integrating traffic monitoring, traffic signage, road lighting, public security monitoring, and other related devices.

Multi-box integration integrates the boxes of traffic monitoring, road lighting, public security monitoring, sensors, and other equipment to reduce the number of road devices and beautify the city space.

5.2
Economic Benefits, Industrial Value and Social Benefits

The construction and deployment of high-level intelligent roads have significant economic benefits, industrial value and social benefits. It can not only meet the development needs of large-scale commercialization of VICAD for the future, but also meet the development needs of low-level autonomous driving and vehicle-to-vehicle communication for the present, supporting the development of intelligent transportation, intelligent traffic management, intelligent highways, smart travel services, and even the construction of new smart cities.

5.2.1 Significant Economic Benefits

With the goal of achieving full L4 autonomous driving, the cost required for the AD technology route is the cost of adding on-board equipment or upgrading systems for all vehicles to L4, while the cost required for the VICAD technology route is approximately equal to the cost of building C4 high-level intelligent roads and upgrading all vehicles to L2+. Comparing the costs required for the two routes can determine the economic viability of each.

(1) Cost required to achieve full L4 autonomous driving with AD technology route

Taking Beijing as an example for estimation, as of the end of 2021, Beijing's total number of vehicles is 6.85 million[32] . Assuming a conservative estimate of the cost required to equip each vehicle with the necessary sensors and 1000 TOPS domain control is around 20,000 yuan per vehicle, the total cost required to achieve full L4 level autonomous driving would be approximately 137 billion yuan.

(2) Cost required to achieve full L4 autonomous driving with VICAD technology route

Based on the VICAD technology route, the condition for achieving full L4 autonomous driving is that all roads and intersections are upgraded to C4 standards, and vehicles are equipped with L2+ or higher-level autonomous driving capabilities. Therefore, the cost required for this route includes the cost of upgrading roads and vehicles:

1) The cost of upgrading vehicles is mainly used to upgrade vehicles to L2+ or higher-level autonomous driving capabilities. In 2021, the overall installation rate of ADAS in commercial vehicles in China is approximately 17.3%. Therefore, out of the 6.85 million vehicles in Beijing, approximately 5.665 million vehicles need to be upgraded, with a cost of approximately 5,000 yuan per vehicle (for sensors, communication equipment, auxiliary driving systems, etc.), resulting in a total incremental cost of approximately 28.325 billion yuan.

2) The cost of upgrading roads mainly includes the cost of upgrading intersections and road sections as well as the operating and maintenance costs of related equipment, systems, and platforms. In terms of the cost of upgrading intersections and road sections, according to the forecast data from CITIC Securities[33] , the average cost of C-V2X transformation for a single intersection in 2020 was approximately 818,400 yuan, and the average cost of C-V2X transformation for each kilometer of highway/fast road was approximately 397,200 yuan. These prices were proposed when the industry was in the early stage of development with small shipment volume. With the full implementation of "new infrastructure," on the one hand, vehicle-infrastructure coordination equipment will evolve from laboratory form to functional mass production, and the construction cost of infrastructure will greatly decrease. On the other hand, benefiting from industrial upgrading and iteration, the industry cost will also continue to decrease, for example, the chip industry's "Moore's Law" is constantly evolving. From the perspective of infrastructure, intelligent computing power continues to develop rapidly, and the scale of infrastructure computing power continues to expand, which will also significantly reduce the investment cost of high-level intelligent roads.

As shown in Figure 5.12, the preliminary estimate for the cost of C-V2X transformation of a single intersection in 2022 is reduced to about 578,400 yuan, and the cost of C-V2X

32. Statistical Bulletin on National Economic and Social Development in Beijing in 2021 issued by the Beijing Municipal Bureau of Statistics and the NBS Survey Office in Beijing.
33. Internet of Vehicles: An Important Direction of New Infrastructure, Pearl of 5G Application published by China Securities Co., Ltd. in March 2020.

transformation per kilometer of highway/expressway is reduced to about 268,800 yuan. The equipment deployment cost per kilometer of urban roads is about 300,000 yuan (due to obstacles on urban roads, the density and quantity of road intelligent devices are higher than those on highways, and the required cost will increase accordingly), and the investment cost of road infrastructure construction is reduced by about 30%. With the upgrading and iteration of the industry and the large-scale landing of vehicle-road coordination and autonomous driving, the construction cost will be further reduced.

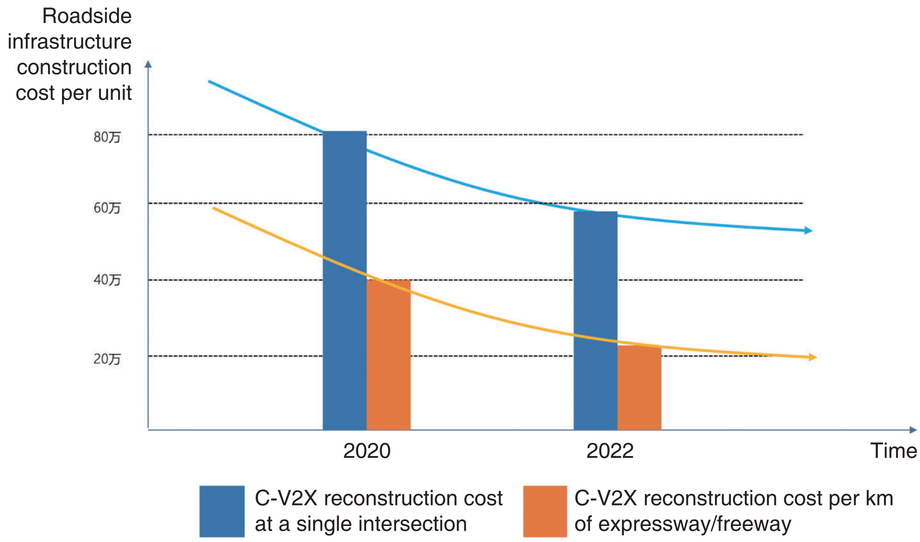


Figure 5.12 Development Trend of Unit Cost of Roadside Infrastructure

In terms of operational costs, there exist regional, project-specific, and company-specific variations in equipment maintenance and operation costs. However, it is generally observed that these costs account for approximately 2% to 3% of the total equipment costs. In this white paper, we have taken the conservative approach and considered these costs to be 3% of the total equipment costs. Therefore, the formula for calculating the cost of constructing an urban C4 road is as follows:

City C4 road construction cost (in yuan) = {number of intersections * intersection unit price (in yuan per intersection) + total highway mileage * mileage unit price (in yuan per kilometer)} * (1 + equipment maintenance cost coefficient). Table 5.7 presents the costs of constructing urban C4 roads for three cities, namely Beijing, Shanghai, and Hangzhou.

Cities	Intersection upgrading and reconstruction costs			Road section upgrading costs			Operation and maintenance cost estimation (100 million yuan)	Total (100 million yuan)
	Intersection number (10,000 pcs)	Average cost (10,000 yuan)	Total (100 million yuan)	Total road mileage (km) [34]	Average cost (10,000 yuan)	Total (100 million yuan)		
Beijing	0.96	57.84	55.53	2.23	30.00	66.90	3.67	126.10
Shanghai	0.70	57.84	40.49	1.31	30.00	39.30	2.39	82.18
Hangzhou	0.58	57.84	33.55	1.69	30.00	50.70	2.53	86.78
Note: The above data is statistical estimates, and the calculation results are for reference only								

Table 5.7 Cost Estimation of Urban C4 Road Construction

For instance, in Beijing, as of the end of 2021, the total mileage of roads (including highways, urban roads, and rural roads) was approximately 22,300 kilometers. Assuming a renovation/construction cost of 300,000 yuan per kilometer, and considering approximately 9,600 intersections in the city, the cost of constructing C4 high-level intelligent roads across the entire city is estimated to be approximately 12.61 billion yuan. The total cost for all vehicles in the city to reach L2+ or above is approximately 28.325 billion yuan. The total cost required to achieve full L4 using the VICAD route is approximately 40.935 billion yuan. From an economic standpoint, the adoption of the VICAD route results in the transfer of high-performance sensors and large computing platforms from vehicles to the roadside, thereby achieving equipment and system reuse and sharing. In contrast to the AD technology route, this approach results in cost savings of approximately 30%.

5.2.2 Enormous Industrial Value

The VICAD system engineering project, as a traction force, not only accelerates the popularization and application of autonomous driving, improves traffic safety and efficiency, but also promotes industrial development. Similar to national major projects such as "two bombs and one satellite" and "aerospace", VICAD can drive the development of basic science, cutting-edge technology, and achieve interdisciplinary integration and innovation application of manufacturing and management systems.

Firstly, VICAD can drive the coordinated development of related industries such as intelligent equipment, map positioning, cloud computing, communication, and security. In the process of large-scale mass production of autonomous driving, industry practitioners and regulatory units are facing a large number of safety issues, especially HD maps, HD positioning, and data closed-loop issues that require high accuracy, real-time and large-scale data transmission. In the current architecture of combining single-vehicle intelligence and vehicle-cloud, safety issues cannot be effectively solved, which has long plagued

34. The Beijing Transportation Development Annual Report in 2021 issued by the Beijing Transportation Development Research Institute, the Shanghai Toll Road Statistical Bulletin in 2021 issued by the Shanghai Municipal Transportation Commission, and the Hangzhou Yearbook - Transportation in 2021 issued by the Hangzhou Municipal Transportation Bureau.

the entire industry. Through VICAD, cross-industry resources can be more systematically integrated to provide inexhaustible power for cross-industry integration and development. In addition, in terms of communication, VICAD is an important application scenario for 5G and C-V2X communication, which will accelerate the evolution of communication technology and industry development. China has already taken the lead in the field of advanced communication technologies such as 5G and C-V2X, establishing a global leading advantage in standards and patents. Currently, there is an urgent need for a fully scalable and widely promising application scenario to support the communication industry's accelerated iterative innovation.

Secondly, developing VICAD and building high-level intelligent roads are the key breakthrough points to solve the current "chip shortage and OS shortage" in China's intelligent industry. From the perspective of demand construction, VICAD provides an important opportunity and window for the development of key links in the intelligent industry chain, such as chips and operating systems. Since the 1980s, the computer industry has experienced two epic waves of personal computer popularity and mobile internet, which have also given birth to the "win-tel alliance" (Microsoft and Intel) in the PC era, and the Arm and Android (Google) in the mobile era. "Chip + OS" firmly controls the key links of the relevant industry chain, forming insurmountable barriers both technically and ecologically. Only the birth of new industries can produce new ecological dominators, and VICAD should shoulder this responsibility. On the other hand, the era of the Internet of Things, in which everything is connected, is unstoppable. Autonomous driving technology driven by artificial intelligence is gradually becoming the biggest factor of change in the transportation industry. The intelligent transportation system is about to usher in the era of "Intelligent Transportation IoT" driven by autonomous driving technology. Billion-level "mobile robots" will soon be connected to an unprecedentedly grand network, bringing opportunities for intelligent industry that will surpass the past.

5.2.3 Potential Social Benefits

The potential social benefits of constructing a C4 level intelligent road can be quantitatively analyzed from three aspects: reducing traffic accidents, easing traffic congestion, and promoting economic growth.

1) The economic benefit of reducing traffic accidents: VICAD can significantly improve traffic safety and reduce traffic accidents, making travel safer. According to the US Department of Transportation's analysis of 6 million vehicle accidents, single-vehicle intelligence can prevent 60% of traffic accidents, and V2X can reduce 81% of traffic accidents[35] . CIDAS (China's in-depth Accidents Survey) data shows (see Figure 5.13) that traffic accidents caused by human factors account for as high as 94%, including driver failure to detect, vision obstruction, misjudgment, and error in operation, etc.[36] VICAD can theoretically avoid all human-caused traffic accidents through collaborative perception, decision-making and control. For conservative estimation, VICAD is assumed to prevent 80% of traffic accidents in the calculation.

35. The research report, the Analysis of V2X Commercial Implementation Path, issued by China Electric Vehicle 100, Intelligent Vehicle and Smart City Collaborative Development Alliance, and Audi (China) Enterprise Management Co., Ltd. in 2021
36. Statistics of China In-Depth Accident Study (CIDAS).

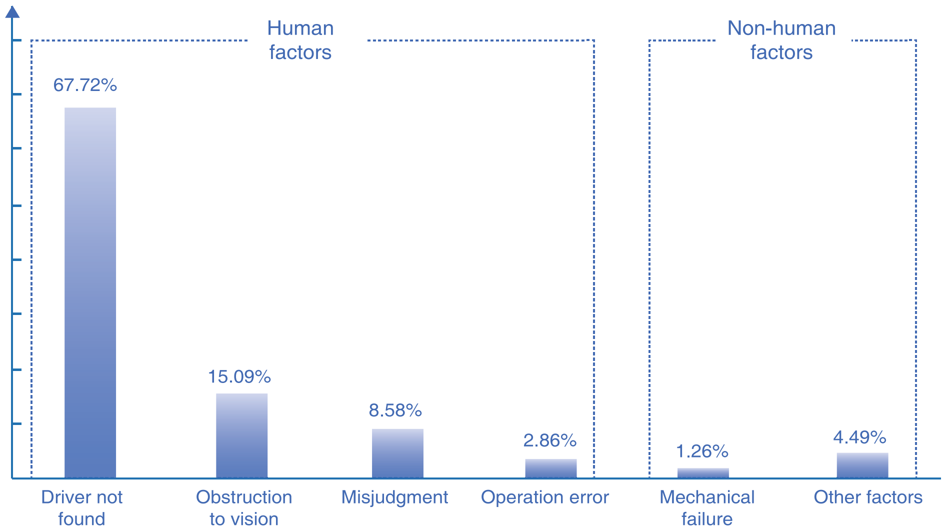


Figure 5.13 CIDAS Accident Cause Data Statistics

The losses caused by traffic accidents are staggering, including loss of wages, medical expenses, legal fees, emergency assistance fees, insurance fees, property damage, and so on. This whitepaper only calculates the direct property damage caused by traffic accidents and the indirect economic losses avoided by reducing fatalities resulting from traffic accidents. The formula for calculating the economic benefits of constructing C4 roads to reduce traffic accidents is as follows:

Annual economic benefits of reducing traffic accidents on C4 roads (in yuan)

= (Direct property damage(yuan) + death toll * death compensation (yuan /person)) * traffic accident prevention rate (%)

2) The economic benefits of reducing traffic congestion and fuel consumption:

The China Intelligent Connected Vehicle Innovation Alliance released a report in 2019 titled "Development Status and Countermeasures of Intelligent Connected Vehicles Industry". The report highlights the potential of vehicle networking technology to improve road traffic efficiency by 10%. The adverse economic impact of traffic congestion is not limited to the cost of fuel consumption but also includes time, carbon emissions, and tailpipe treatment costs. The calculation of economic losses caused by traffic congestion mainly focuses on estimating fuel consumption due to congestion, as GDP may also be generated during the same time period as the time and treatment costs of congestion.

The report cites statistics indicating that fuel consumption during idling in traffic jams is equivalent to driving 1 kilometer normally every 3 minutes. Based on an average fuel consumption rate of 8 liters/100 kilometers per vehicle, the fuel consumption every 3 minutes during traffic congestion is estimated to be 0.08 liters. Additionally, considering that each vehicle is stuck in traffic for an average of 30 minutes per day[37] , the average additional fuel consumption per vehicle due to traffic congestion is estimated to be 0.8 liters per day.

Using the current price of 92 gasoline, the number of urban motor vehicles, the average vehicle usage rate, and other indicators, this calculation assumes a 10% average reduction in traffic congestion on C4 high-level intelligent road. The economic benefits of fuel consumption savings are then calculated:

Annual economic benefits of reducing traffic congestion and fuel consumption on C4 roads (in yuan) =
(Additional fuel consumption in congestion (liters/car-day) * Price of 92 gasoline (yuan/liter) * Number of motor vehicles*
Average departure rate (%) * Number of days per year * Reduction rate of traffic congestion (%))

3) The economic benefits of promoting economic growth:

The integration and coordination of transportation participants, vehicles, and facilities has become a major trend in the development of transportation systems. Research on technologies such as vehicle-infrastructure coordination is also trending towards the integration of vehicle-infrastructure-cloud intelligent transportation systems, which can achieve comprehensive optimization of traffic control and intelligent decision-making, strengthen the intelligent coordination and control of urban comprehensive transportation, improve the efficiency of urban traffic flow and comprehensive service level, and enhance transportation efficiency. In 2019, the China Intelligent Connected Vehicle Innovation Alliance released the "Development Trends and Countermeasures of the Intelligent Connected Vehicle Industry", stating that the vehicle networking technology can improve road traffic efficiency by 10%. Referring to "The Impact of Comprehensive Transportation Efficiency on Economic Growth in Urban Agglomerations: A Comparative Study Based on the Yangtze River Delta and the Guangdong-Hong Kong-Macao Greater Bay Area"[38] , for every 1% improvement in comprehensive transportation efficiency, the promotion effect on local economic growth in the Yangtze River Delta and Guangdong-Hong Kong-Macao are 0.076% and 0.069%, respectively. The comprehensive transportation system is a complex system composed of multiple transportation modes. Based on the indicators selected in the referenced literature, this study estimates the proportion of different transportation modes based on the output variable indicator of passenger and freight volume, which reflects the scale level. The contribution of passenger transportation (in 10,000 person-times) and freight transportation (in 10,000 tons) to GDP growth differs. To facilitate estimation, this study assumes that the coefficient ratio of the two is 1. Based on the data of passenger and freight transportation volume in Beijing, Shanghai, and Hangzhou[39 40], the estimated proportion of different transportation modes in the comprehensive transportation system is shown in Table 5.8.

37. The Traffic Analysis Report in China's Major Cities (Q3 of 2018) jointly issued by Amap with the Joint Laboratory for Future Transport and Urban Computing, the Tsinghua University - Daimler Sustainable Transportation Research Center, Alibaba Cloud and other units.
38. The Impact of Comprehensive Transportation Efficiency of Urban Agglomeration on Economic Growth - Based on the Comparative Study of the Yangtze River Delta and Guangdong-Hong Kong-Macao Greater Bay Area
39. The Beijing Statistical Yearbook in 2021 issued by the Beijing Municipal Bureau of Statistics, the Shanghai Statistical Yearbook in 2021 issued by the Shanghai Municipal Bureau of Statistics, and the Hangzhou Statistical Yearbook in 2021 issued by the Hangzhou Municipal Bureau of Statistics
40. Pipeline freight volume data in the Beijing Statistical Yearbook in 2021 issued by the Beijing Municipal Bureau of Statistics

Transportation modes	The proportion of different transportation modes in Beijing				The proportion of different transportation modes in Shanghai				he proportion of different transportation modes in Hangzhou			
	Passenger traffic volume (10,000 person-times)	Freight volume (10,000 tons)	Total passenger and freight volume	Proportion	Passenger traffic volume (10,000 person-times)	Freight volume (10,000 tons)	Total passenger and freight volume	Proportion	Passenger traffic volume (10,000 person-times)	Freight volume (10,000 tons)	Total passenger and freight volume	Proportion
Highway	24548.00	21789.00	46337.00	0.74	1332.00	46051.00	47383.00	0.31	4535.00	34837.00	39372.00	0.73
Railway	6383.00	360.00	6743.00	0.11	7605.00	478.00	8083.00	0.05	5895.00	578.00	6473.00	0.12
Aviation	5339.00	147.00	5486.00	0.09	3021.00	403.00	3424.00	0.02	1414.00	46.00	1460.00	0.03
Waterway	-	4049.00	4049.00	0.06	15.00	92294.00	92309.00	0.61	339.00	6483.00	6822.00	0.13
Total	36270.00	26345.00	62615.00		11973.00	139226.00	151199.00		12183.00	41944.00	54127.00	
Note: The above data is based on statistical estimates and the calculation results are for reference only												

Table 5.8 Estimated Proportion of Different Transportation Modes in Comprehensive Transportation

The calculation formula for the benefits of promoting economic growth through the construction of C4 roads is as follows:

Annual economic growth benefits of C4 road (in yuan)
= Promoting effect on economic growth per 1% increase (%) * Gross Domestic Product (GDP) of the region (in yuan) * Comprehensive improvement rate of transportation efficiency (%) * Proportion of highway transportation and transportation (in %).

Therefore, for Beijing, Shanghai, and Hangzhou, the benefits brought by the construction of C4 roads were calculated using investment return rate and internal return rate[40] , as shown in Tables 5.9 and 5.10.

Cities	Annual cost of building C4 intelligent roads (in billions of yuan)		Annual comprehensive investment yield of C4 intelligent roads (in billions of yuan)				
	Total (100 million yuan)	Device economic life amortized over 5 years (in billions of yuan per year)	Total economic benefits of reduced traffic accidents (100 million yuan/ year)	Total economic benefits of reduced traffic congestion and fuel consumption (100 million yuan/year)	Total benefits of the economic growth driven by the improved comprehensive transportation efficiency (100 million yuan/ year)	Total comprehensive economic profits (100 million yuan/ year)	Comprehensive investment yield (%)
Beijing	126.10	25.22	12.05	8.22	205.62	225.89	795.68%
Shanghai	82.18	16.44	10.76	7.34	101.81	119.91	629.56%
Hangzhou	86.78	17.36	2.68	4.40	100.47	107.55	519.67%
Note: The above data is based on statistical estimates and the calculation results are for reference only.							

Table 5.9 Estimation of Return on Investment of C4 Roads in Cities

Cities	Initial cost (100 million yuan)	Profits in the 1st year (100 million yuan)	Profits in the 2nd year (100 million yuan)	Profits in the 3rd year (100 million yuan)	Profits in the 4th year (100 million yuan)	Profits in the 5th year (100 million yuan)	Internal rate of return (IRR; %)
Beijing	-126.1	225.89	225.89	225.89	225.89	225.89	178.06%
Shanghai	-82.18	119.91	119.91	119.91	119.91	119.91	144.23%
Hangzhou	-86.78	107.55	107.55	107.55	107.55	107.55	121.62%
Note: The above data is based on statistical estimates and the calculation results are for reference only.							

Table 5.10 Estimation of Internal Rate of Return of C4 Roads in Cities

Take Beijing as an example:

1) The construction of C4 roads incurs a total cost of approximately 12.61 billion yuan. Following the equipment's economic lifespan of five years, the annual investment cost would be about 2.522 billion yuan[41].

2) Over a five-year span, the C4 roads in Beijing yields an average annual economic benefit of about 22.589 billion yuan. The comprehensive investment return rate reaches an impressive 795.68%, and the internal rate of return (IRR) is at 178.06%.
The economic analysis demonstrates that constructing C4 roads can provide notable economic advantages. Furthermore, the deployment of high-level intelligent roads can bring forth other economic benefits, such as:

(1) Preventing redundant investment in construction: High- level intelligent roads possess the ability to perceive and recognize high-precision information in full-scale. This capability enables the full utilization of the road system and equipment facilities. Providing capabilities such as traffic monitoring and law enforcement, public opinion monitoring, and public safety management to multiple government departments such as transportation, public security, and urban construction based on the intelligent road's capabilities can offer basic data and services. Consequently, the maximum use of equipment facilities is achieved, and redundant investment in construction and equipment waste is avoided.

(2) Exploring additional service and business models through innovative applications: High-level intelligent roads converge and process high-dimensional data in real-time from vehicles, roads, pedestrians, and clouds, among other sources. In addition to serving vehicle-road coordination and autonomous driving, they can be utilized to explore commercial operational service innovations, such as smart traffic management services, urban smart travel, and vehicle safety management. These services can be leveraged to generate profitability for high-level intelligent roads, thereby maximizing the value of the intelligent road system.

41. The calculation of investment income is estimated according to the plan of investing in place once in a 5-year investment cycle. The actual construction experience is the construction of the demonstration area in the early stage, the construction of the pilot area, the promotion and deployment in the mid-term, and the gradual promotion of the high-speed development in the later stage. If estimated according to the gradual construction model, the economic return index will be better than the result of this simplified calculation. This estimate is based on It is calculated towards the worse side, but the calculation of this indicator will not cause a large deviation to the conclusion of the argument.

5.3
China's Advantages in Constructing High-Level Intelligent Roads

China has made remarkable progress in the development of vehicle-infrastructure cooperation in recent years, and has established itself as a leader in this field. This has given China certain advantages in developing and building high-level intelligent roads, which could not only serve autonomous driving, but also leverage the full potential of intelligent roads. These roads possess the ability to provide high-precision perception of all elements, vehicle-infrastructure cooperative decision-making and planning, and control, thereby providing the necessary conditions for intelligent management, intelligent control, and smart services for transportation. They can also support the development of innovative applications and smart services, such as shared travel, autonomous parking, smart logistics, and transportation operators. Furthermore, the construction of high-level intelligent roads could significantly contribute to the realization of China's grand goal of building a strong transportation country, promoting economic transformation and upgrading, and achieving high-quality development

(1) National overall planning capabilities at the institutional mechanism level

At the institutional mechanism level, China has a distinct advantage in terms of its national coordination capability. The country's national conditions provide it with a strong overall coordination capability, which can be effectively utilized to call for and lead the development of new technologies at various stages. This coordination capability is particularly evident in the research and implementation of vehicle-to-road coordination and autonomous driving. For instance, the national or local government can facilitate technological research and development by formulating preferential policies, approving the establishment of testing and demonstration zones, and leading cooperation with large companies. Moreover, China has the potential to fully exploit its institutional mechanism advantages, policy advantages, and technological and industrial advantages in order to accelerate the re-planning and upgrading of road infrastructure nationwide.

Category	Cities	Real-time performance
Vehicle to Everything pilot areas/ demonstration areas	Wuxi	National Vehicle to Everything Pilot Area in Jiangsu Province (Wuxi)
	Tianjin	National Vehicle to Everything Pilot Area in Tianjin (Xiqing District)
	Changsha	National Vehicle to Everything Pilot Area in South Changsha
	Chongqing	National Vehicle to Everything Pilot Area in Chongqing (Liangjiang New Area)
	Three provinces and one city in the Yangtze River Delta	National Vehicle to Everything Pilot Area in the Yangtze River Delta
	Suzhou	Vehicle to Everything Pilot Area in Suzhou

	Nanjing	Provincial Vehicle to Everything Pilot Area in Nanjing
	Liuzhou	Vehicle to Everything Pilot Area in Liuzhou (under construction)
	Beijing	Beijing High-level Automated Driving Demonstration Area (note: the first in the world)
	Beijing and cities in Hebei province	National Intelligent Vehicle and Smart Transportation (Beijing-Hebei) Demonstration Area
	Changchun	National Intelligent Connected Vehicle Application (Northern) Demonstration Area
	Shanghai	National Intelligent Connected Vehicle (Shanghai) Pilot and Demonstration Area
Vehicle to Everything pilot areas /demonstration areas	Wuhan	National Intelligent Connected Vehicle (Wuhan) Testing and Demonstration Area
	Hangzhou and Jiaxing	5G Vehicle to Everything Application Demonstration Area in Zhejiang Province
	Guangzhou	Guangzhou Intelligent Connected Vehicle and Smart Transportation Application Demonstration Area
	Chongqing	National Intelligent Vehicle Integrated Test Area (i-VISTA)
	Shanghai	Lingang Intelligent Connected Vehicle Comprehensive Testing and Demonstration Area in Shanghai
	Shanghai	Comprehensive Demonstration Testing Area/Base of "Vehicle-infrastructure-network-cloud Integration" Based on Intelligent Vehicle
Cloud Control Platform	Changsha	National Intelligent Connected Vehicle (Changsha) Testing Area
	Wuxi	National Intelligent Transportation Comprehensive Test Base (Wuxi)
	Chengdu	Sino-German Cooperated Intelligent Connected Vehicle (Vehicle to Everything) Test Base in Sichuan
	Beijing	National Operating Vehicle Autonomous Driving and Vehicle-infrastructure Collaboration Testing Base in Tongzhou District, Beijing
	Chongqing	Demonstration Base for Autonomous Driving Test and Application of Chongqing Vehicle Testing and Research Institute
	Xi'an	Vehicle to Everything and Intelligent Vehicle Testing Ground of Chang 'an University
	Taixing	Intelligent Connected Vehicle Autonomous Driving Closed Field Testing Base (Taixing)
	Xiangyang	Intelligent Connected Vehicle Automatic Driving Closed Field Testing Base (Xiangyang)

Urban Smart Vehicle Infrastructure and Mechanism Construction Pilot	Ningbo, Quanzhou, Putian, Wuhan, Deqing and Guangzhou
Smart City Infrastructure and Intelligent Connected Vehicles ("Dual Intelligence") Collaborative Development Pilot	Beijing, Shanghai, Guangzhou, Wuhan, Changsha, Wuxi, Chongqing, Shenzhen, Xiamen, Nanjing, Jinan, Chengdu, Hefei, Cangzhou, Wuhu and Zibo

Table 5.11 Pilot Areas/Demonstration Areas of National Intelligent Connected Vehicle

(2) At the policy level, comprehensive development of VICAD is accelerated by national new infrastructure policies.

At the national strategic level, China has identified the development technology route of intelligent connected vehicles empowered by single-vehicle intelligence and network connection. In the field of single-vehicle intelligence, the gap between China and the United States is gradually narrowing, but considering that China's road conditions and traffic environment are more complex, VICAD has more advantages and can be leveraged as a focus point for China's autonomous driving to overtake.

At the policy level, the competent national authorities coordinate planning, strengthen top-level coordination, and create a good environment for industrial development. Local government departments at all levels also actively promote the development of VICAD industry in combination with their own development needs and basic advantages. In recent years, the national level has issued a series of top-level planning and design documents, such as the "Intelligent Vehicle Innovation and Development Strategy," "National Comprehensive Three-Dimensional Transportation Network Planning Outline," and "Outline of Building a Strong Transportation Country." At the local government level, Jiangsu Province has formulated and issued the "Key Tasks Decomposition Table for Jiangsu Province's Connected Vehicle Industry Development (2020-2021)," Tianjin has issued the "Tianjin Connected Vehicle (Intelligent Connected Vehicle) Industry Development Action Plan," Shanghai has issued the "14th Five-Year Plan for Advanced Manufacturing Development in Shanghai," focusing on the development of new energy vehicles, intelligent connected vehicles, vehicle and parts manufacturing, and Guangdong Province has issued the "14th Five-Year Plan for High-Quality Development of Manufacturing Industry," supporting the development of intelligent connected vehicle perception, control, execution, vehicle information and entertainment systems, promoting the construction of automobile testing and testing sites, and actively promoting the

Time	Issue unit	Document name
December 2019	The Central Committee of the Communist Party of China and the State Council	Program of Building National Strength in Transportation
February 2021	The Central Committee of the Communist Party of China and the State Council	National Comprehensive Three-dimensional Transportation Network Planning Outline
March 2021	28 departments and units including the National Development and Reform Commission and the Ministry of Industry and Information Technology	Implementation Plan for Accelerating the Cultivation of New Types of Consumption
April 2021	Ministry of Public Security	Road Traffic Safety Law of China (Revised Draft)
April 2021	Ministry of Industry and Information Technology	Intelligent Connected Vehicle Manufacturing Enterprises and Product Access Management Guide(Trial) (Draft for Comments)
July 2021	Ministry of Industry and Information Technology	Three-Year Action Plan for the High-quality Development of the Cybersecurity Industry (2021-2023) (Draft for Comment)
July 2021	10 departments and units including the Ministry of Industry and Information Technology, the Office of the Central Cyberspace Affairs Commission, and the National Development and Reform Commission	5G Application "Sailing" Action Plan (2021-2023)
July 2021	The Ministry of Industry and Information Technology, the Ministry of Public Security, and the Ministry of Transport	Management Specifications for Road Testing and Demonstration Application of Intelligent Connected Vehicles (Trial)
August 2021	Ministry of Industry and Information Technology	Opinions of the Ministry of Industry and Information Technology on Strengthening the Management of Intelligent Connected Vehicle Manufacturers and Product Access
August 2021	The Ministry of Transport, and the Ministry of Science and Technology	Opinions on Driving and Accelerating the Construction of a Country with Strong Transportation Strength by Scientific and Technological Innovation
December 2021	Ministry of Industry and Information Technology	Notice on Strengthening Vehicle to Everything Network Security and Data Security Work
December 2021	Ministry of Industry and Information Technology	Notice on Strengthening the Management of Real-name Registration of Vehicle to Everything Cards
December 2021	Ministry of Transport	Digital Transportation Development Planning - Action Plan for New Infrastructure Construction in the Field of Transportation (2021-2025)
October 2021	Ministry of Transport	Digital Transportation Development Plan During the 14th Five-Year Plan Period

November 2021	Ministry of Industry and Information Technology	Information and Communication Industry Development Plan for the "14th Five-Year Plan" Period
January 2022	Ministry of Transport	Notice on Issuing the Green Transportation Development During the 14th Five-Year Plan Period
January 2022	State Council	Circular of the State Council on Printing and Issuing the Development Plan for the Modern Comprehensive Transport System During the 14th Five-Year Plan Period
March 2022	Ministry of Transport	Notice on Issuing the Evaluation Index System for Building National Strength in Transportation
April 2022	The Ministry of Transport, and the Ministry of Science and Technology	Notice on Issuing the Outline of Medium and Long-term Development Plan for Scientific and Technological Innovation in the Transportation Field (2021-2035) (Wuxi)
April 2022	The Ministry of Transport, and the Ministry of Science and Technology	Notice on Issuing the Scientific and Technological Innovation Planning in the Transportation Field During the 14th Five-Year Plan Period
July 2022	The Ministry of Science and Technology, the Ministry of Education Ministry of Industry and Information Technology, the Ministry of Transport, the Ministry of Agriculture and Rural Affairs and the National Health Commission	The Guiding Opinions on Accelerating Scenario Innovation and Promoting High-quality Economic Development with High-level Application of Artificial Intelligence
August 2022	Ministry of Science and Technology	Notice on Supporting the Construction of New Generation Artificial Intelligence Demonstration Application Scenarios
November 2022	The Ministry of Industry and Information Technology and the Ministry of Public Security	Notice on Carrying out the Pilot Program of Access and Passage of Intelligent Connected Vehicles (Draft for Comment)
December 2022	The Central Committee of the Communist Party of China and the State Council	Outline for the Strategic Plan to Expand Domestic Demand (2022-2035)

Table 5.12 Policies on intelligent connected vehicles released by the government in the past three years.

(3) At the industrial level, the automotive, 5G, road, and ICT industries in China possess the conditions for innovative leadership.

The country enjoys significant advantages in the automotive, transportation, and ICT technologies and industries, which, through the deep integration and coordination of vehicle-road synergy and autonomous driving, have formed a united front and initially possess the conditions for innovative and leading development

In the automotive and transportation markets, China's automotive and transportation market scales have been among the world's largest, with the country's annual automobile production and sales reaching 26.082 million and 26.275 million units in 2021, respectively, maintaining the first place in global automobile production and sales for thirteen consecutive years. Among them, the production and sales of new energy vehicles were 3.545 million and 3.521 million units, respectively, ranking first in the world for seven consecutive years and continuing to consolidate China's position as the world's largest automobile market[42]. By the end of 2020, China's total road mileage exceeded 5.198 million kilometers, and the scale of the road network continued to improve, with the total length of expressways exceeding 160,000 kilometers, ranking first in the world. The country's main highway network has been basically completed, covering about 99% of the urban population of cities with a population of over 200,000 and prefecture-level administrative centers. China's large-scale automotive and transportation market plays an important leading role in the global market, and the country can fully utilize its market advantages to formulate market rules and technical standards with Chinese characteristics in accordance with its own needs, thereby gaining valuable discourse power in the future competition

In terms of the automobile and transportation market, China's automobile and transportation market ranks among the top in the world. In 2021, the annual production and sales of automobiles in China will be 26.082 million and 26.275 million respectively, maintaining the world's largest automobile production and sales for 13 consecutive years. The production and sales of energy vehicles were 3.545 million and 3.521 million respectively, ranking first in the world in sales for seven consecutive years, continuing to consolidate China's position as the world's largest automobile market, and at the same time continue to move towards the world's automobile power. By the end of 2020, the total mileage of China's expressways will exceed 5.198 million kilometers, and the scale of the road network will continue to increase. Among them, the total mileage of expressways will exceed 160,000 kilometers, ranking first in the world. The main line of the national expressway network will be basically completed, covering about 99% of the urban population20 More than 10,000 cities and prefecture-level administrative centers. China's ultra-large-scale automobile and transportation markets play an important leading role in the global market. China can make full use of its own market advantages, formulate market rules and technical standards with Chinese characteristics according to its own needs, and win a valuable voice in future competitions.

In terms of 5G communication, combining AI-powered intelligent bicycles with 5G enables the installation of a 360-degree "thousand-mile eye" and a "smart brain" that oversees the entire system on intelligent vehicles, achieving interconnectivity and inter-control of vehicles, roads, people, and infrastructure. As of the end of 2021, China had built and opened 1.425 million 5G base stations, accounting for over 60% of the world's total and having established the world's largest 5G network, covering all urban areas of prefecture-level cities, over 98% of county-level cities, and 80% of townships and towns[43] , providing communication guarantees for achieving interconnectivity of vehicles, roads, people, and other things.

42. People's Daily (January 13, 2022): China's Automobile Production and Sales Volume has Remained the First in the World for 13 Consecutive Years http://www.news.cn/fortune/2022-01/13/c_1128257359.htm
43. People's Daily (February 8, 2022): The total number of 5G base stations in China accounts for over 60% of the world. http://www.gov.cn/xinwen/2022-02/08/content_5672469.htm

(4) At technical support level, the standard system of the vehicle-infrastructure-cloud is fully equipped.

In June 2018, the Ministry of Industry and Information Technology and the National Standardization Management Committee jointly completed the formulation and issuance of a series of documents entitled "Guidelines for the Construction of National Vehicle Internet of Things Industry Standard System" (as shown in Figure 5.14), which clarified the top-level design ideas for the country to build a vehicle Internet of Things ecological environment, indicating the strategic intention to actively guide and promote cross-domain, cross-industry, and cross-departmental cooperation. The series of documents include overall requirements, intelligent connected vehicles, intelligent transportation, vehicle intelligent management, information communication, and electronic products and services. The system planning for the five volumes has been officially released, and the core technical standards of the LTE-V2X-based access layer, network layer, message layer, and security in the information communication standard system have been developed, while LTE-V2X equipment specifications, testing methods, and other standards have also been developed. The technical standard system has basically taken shape, laying a solid foundation for the development of vehicle-road collaboration and autonomous driving.

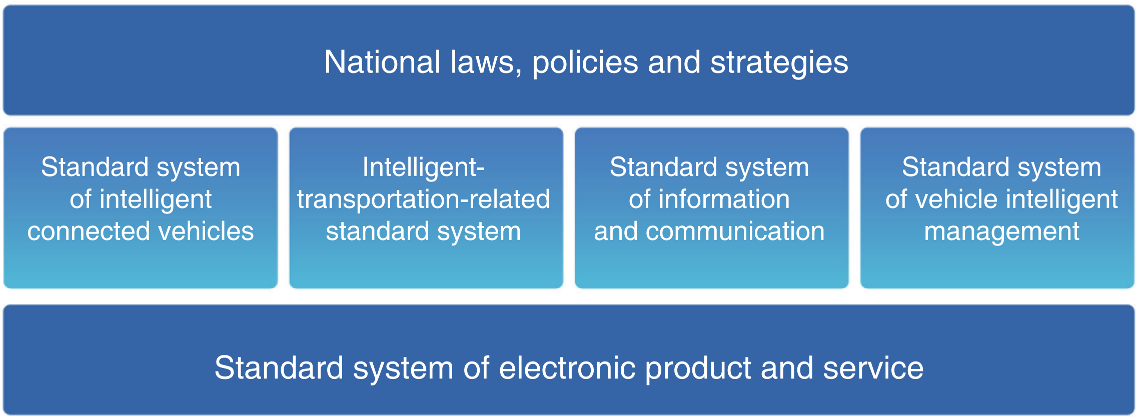


Figure 5.14 Overall Architecture of Standard System in the National V2X Industry

06

Exploration and Practice of Baidu Apollo's VICAD

6.1
Progress of Baidu Apollo's VICAD

6.1.1 Applicable Standards

To fully support Baidu Apollo autonomous driving and ACE intelligent transportation, and to achieve technological leadership and project implementation, Baidu places great importance on and comprehensively deploys vehicle-infrastructure cooperation, autonomous driving, and intelligent transportation standards at all levels, both domestically and internationally. These standards cover V2X communication, automobiles, transportation, artificial intelligence, data, maps, information security, and other professional fields.

Currently, Baidu has issued over 10 different standards, such as the Data Exchange Standard for High-Level Automated Driving Vehicles Based on Cooperative Intelligent Transportation Systems (YD/T3978-2021). Baidu has also participated in and led the formulation of over 200 standards, including the Standard for Test Methods of Automotive Lidar Performance (Chinese Standard), Intelligent Connected Vehicle Automatic Driving System Data Recording Performance Requirements and Test Methods (Chinese Standard), Intelligent and Connected Vehicle - Performance Requirements and Test Methods for Automatic Parking System (Chinese Standard), Technical Requirements for Information Interaction of Vehicle Infrastructure Cooperative Systems (Chinese Standard), and other series of standards.

In the future, Baidu will rely on its technology accumulation in the fields of autonomous driving, intelligent transportation, and AI to support and guide the construction of autonomous driving and road intelligence standards, as well as the industrial development.

Table 6.1 shows the vehicle-infrastructure cooperation standards led by Baidu (deep participation).

SN	Standard name	Standard category	Standard state
1	Data Exchange Standard for High Level Automated Driving Vehicle Based on Cooperative Intelligent Transportation System (YD/T 3978-2021, T/ITS 0135-2020 and CSAE 158-2020)	Industry standards / group standards	Issued
2	Technical Requirements for Information Interaction of Vehicle Infrastructure Cooperative System - Part 1: Roadside Facilities and Cloud Control Platform (T/— 0180.1— 2021)	National standards / group standards	Chinese standards under discussion / group standards issued

3	Technical Requirements for Information Interaction of Vehicle Infrastructure Cooperative System - Part 2 Cloud Control Platform and Third Party Application Service (T/— 0180.2— 2021)	National standards / group standards	Chinese standards under discussion / group standards issued
4	Technical Requirements for Information Interaction of Vehicle Infrastructure Cooperative System - Part 3: Between Roadside Facilities	National standards / group standards	Under compilation
5	Cooperative Intelligent Transportation System - Vehicular Communication Application Layer Specification and Data Exchange Standard (Phase II) (CSAE 157-2020)	Group standard	Issued
6	Technical Requirements for Roadside Perception and Positioning of Autonomous Driving	Group standard	Under compilation
7	Vehicle-infrastructure Collaboration - Edge Computing Facilities (series of standards)	Group standard	Under compilation
8	Technical Guidelines for Auxiliary Facilities of Highway Engineering Adapting to Autonomous Driving	Industry standard	Under compilation
9	Highway Intelligent Digital Technical Specifications	Industry standard	Under compilation
10	Intelligent and Connected Vehicles - General Requirement of Data	National standard	Under compilation
11	Vehicle-infrastructure Collaboration - Roadside Perception System Method (series of standards)	Industry standards / group standards	Under compilation
12	Vehicle-infrastructure Collaboration - Roadside LidarTest Method	National standard	Under compilation
13	5G-based Remote Control Driving Service Requirements - Cloud Control of Self-driving Taxis	Group standard	Under compilation
14	Test Method of MEC Platform for LTE-based Vehicular Communication	Group standard	Under compilation
15	Technical Requirements of V2I Basic Information Unicast of LTE-based Vehicular Communication	Industry standard	Under compilation
16	Intelligent Connected Vehicle Operation Safety Semi-open Road Test Scenario Elements and Setting Requirements	National standard	Under compilation

Table 6.1 Important Standards for Vehicle-infrastructure Collaboration Led by Baidu (Deep Participation)

6.1.2 Apollo Air Program

In May 2021, Baidu and Tsinghua AIR officially launch the Apollo Air program. The program is characterized by three typical features: (1) relying on pure roadside perception to achieve Vehicle-Infrastructure coordination for autonomous driving, (2) continuously reducing dimensionality to support Vehicle-Infrastructure coordination applications, and (3) implementing industry-wide sharing through standardization, open sourcing, and openness.

The greatest technological innovation of Apollo Air is the achievement of closed-loop L4 autonomous driving by relying solely on lightweight continuous perception at the roadside, without the need for onboard perception. As of April 2022, Apollo Air has accumulated over 30,000 kilometers of closed-loop testing (including simulation), with a 99% success rate at intersections. Roadside perception based on Apollo Air has the following outstanding advantages:

(1) End-to-end latency meets the requirements of on-board fusion

The roadside and on-board systems are aligned to meet real requirements, and latency metrics are reasonably allocated to each link: 1) the latency of roadside perception fusion is 140ms, mainly achieved through edge computing, high-performance AI models, and parallelization of local HD maps; 2) the latency of air interface transmission is 50ms, mainly achieved by limiting packet length at the LTE-V2X network layer, optimizing lower-layer transmission methods, and compressing frames within and between frames; 3) on-board preprocessing takes 10ms, compensating for packet loss with trajectory prediction models; the total end-to-end latency is approximately 200ms.

(2) Roadside perception accuracy meets on-board requirements

The perception accuracy of the roadside system fully meets the requirements of the on-board system, with real-time and accurate perception of all traffic elements (including motor vehicles, non-motorized vehicles, pedestrians, obstacles, etc.). The accuracy and recall rate of traffic element perception are both greater than or equal to 95%, and the perception positioning accuracy is 0.5 m (mean), with a speed accuracy of 1.5 m/s (mean) and an object detection rate of less than 2%.

(3) Establishment of a quality evaluation closed-loop system

During the practice of Apollo Air, the roadside data quality evaluation system has gradually been established, which can dynamically evaluate whether the quality of each point meets the requirements of L4 vehicles. Points that meet the requirements of data quality evaluation can support the completion of the Apollo Air closed loop, which means that the point can support "pure roadside perception for Vehicle-Infrastructure coordination for autonomous driving." Figure 6.1 shows one of the standard intersections currently under construction in Yizhuang that meets the requirements of Apollo Air.

Figure 6.1 L4 Automatic Driving Closed-loop of Pure Roadside Perception Based on Apollo Air

6.1.3 Baidu Apollo's Open Platform and Operating System

"Open capabilities, shared resources, accelerated innovation, and sustained mutual benefit" have always been Baidu's technology philosophy. The development of Baidu's VICAD has also consistently adhered to the concept of open source. In December 2019, Baidu Apollo officially released the Vehicle-Infrastructure Cooperative Open Platform 1.0, which is the first domestic open platform for Vehicle-Infrastructure Cooperation. On April 19, 2022, Baidu Apollo upgraded and released the Vehicle-Infrastructure Cooperative Open Platform 2.0 - " Kailu" for the traffic and automotive industry. This marks Baidu Apollo's upgrade from "autonomous driving openness" to "comprehensive openness of autonomous driving and VICAD."

"Kailu" is a complete open software and service system, consisting of three main parts: roadside software platform, roadside reference hardware, and cloud service platform. " Kailu" opens basic capabilities such as perception, prediction, mapping, and calibration, provides technical guidelines and integration specifications for equipment and hardware partners, and shares scene resources in combination with Baidu's extensive user outreach on the vehicle side.

"Kailu" opens Baidu's full-stack vehicle-infrastructure cooperative technology developed since 2016 to the industry, establishing a cooperation-based benign ecosystem and promoting the widespread application of vehicle-infrastructure cooperative technology. It provides a complete framework to support rapid development, achieve digital, networked, and automated application ecology and effects, help developers reduce costs, and improve innovation efficiency. It also leverages Baidu's technical advantages in the field of artificial intelligence to meet the needs of intelligent application development.

Figure 6.2 Overall Architecture of Vehicle-infrastructure Collaboration Open Platform 2.0

On August 1, 2022, Baidu Apollo and Tsinghua AIR jointly released the world's first Open-Source Edge Operating System for Intelligent Road (referred to as ZhiluOS below). It is centered on open source, independent controllability, and networked ecology, and completely opens the core technology of roadside OS for high-level autonomous driving and intelligent transportation. It builds a new open-source and open platform, constructs a new independent controllable high ground, and promotes the diversified and large-scale development of the intelligent networked industry.

ZhiluOS is a basic software platform of roadside edge computing units precipitated under the overall architecture of the "vehicle-infrastructure-cloud integrated control system," driven by high-level autonomous driving technology and applications. It is composed of three parts from the bottom up: kernel layer, hardware abstraction layer, and middleware layer.

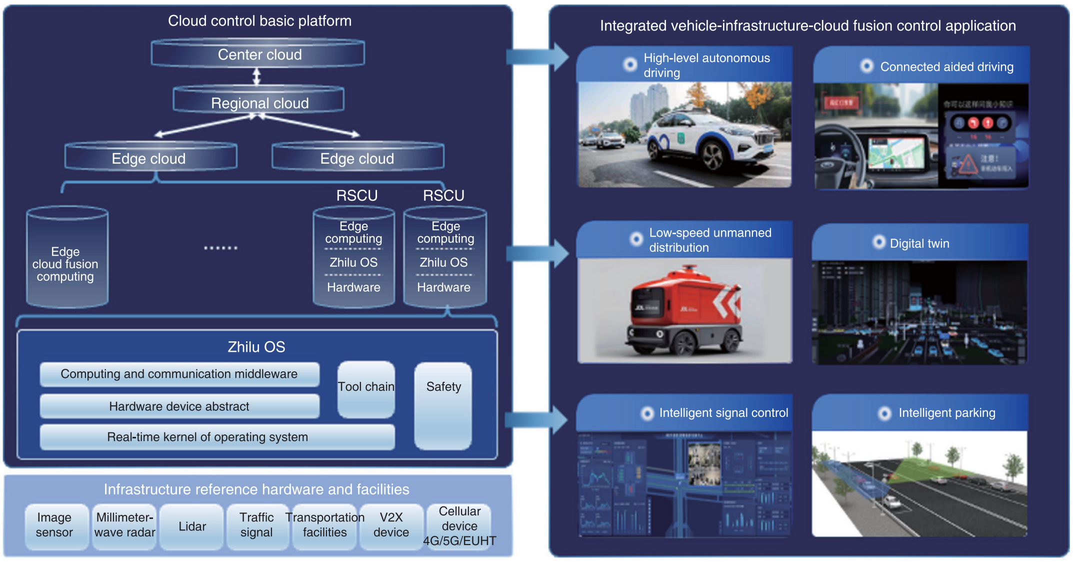


Figure 6.3 Industry Application of Zhilu OS

ZhiluOS is aimed at intelligent networked, high-level autonomous driving, and digital traffic management scenarios, building a unified data and technology foundation and breaking through the ecological island. Facing the industry, ZhiluOS opens full-stack technology, breaks through the industrial bottleneck of "lacking cores and spirits," and accelerates independent controllable upgrading and iteration. Facing city managers, ZhiluOS carries the upgrade demands of various application scenarios for infrastructure and achieves software empowerment for networked traffic management. Facing the ecology, ZhiluOS helps intelligent networked ecosystem manufacturers achieve standardized and efficient innovation and accelerate commercialization.

ZhiluOS supports manufacturers to rapidly develop and reduce costs, accelerate commercialization, and face the hardware ecology with the characteristics of "high intelligence, high performance, high reliability, and localization." It supports domestically made chips driven by domestic souls and helps the hardware ecology explore innovation. Currently, more than 50 industry organizations and companies have become the first batch of ecological partners of ZhiluOS, jointly building a new intelligent networked ecology.

6.1.4 DAIR-V2X Open Dataset

In February 2022, five organizations, including Baidu Apollo, Tsinghua AIR, Beijing Academy of Artificial Intelligence, Beijing Connected and Autonomous Vehicles Technology Co., Ltd., and Beijing High-level Autonomous Driving Demonstration Area, jointly released the DAIR-V2X dataset. This dataset is the first real-world V2X dataset designed for the study of vehicle-infrastructure cooperative autonomous driving. It is a large-scale collection of data elements captured from real-life scenarios and is multi-modal and multi-view. The dataset is equipped with 2D and 3D annotations and has undergone desensitization and security encryption for enhanced privacy and protection. The dataset is available at https://thudair.baai.ac.cn/index and can be accessed within the mainland of China.

Typical features	Feature description
Large scale	The dataset comprises over 70,000 images and 70,000 point clouds, which are distributed among the following components: 1) Infrastructure part: 10,084 images and 10,084 point clouds. 2) Vehicle part: 22,325 images and 22,325 point clouds. 3) Vehicle-infrastructure cooperative part: 38,845 images and 38,845 point clouds. 4) Rope3D part: 50,009 images.
Multiple views and multiple modalities	1) The dataset contains multi-view data captured from both infrastructure and vehicle perspectives, along with 3D annotations for 10 object classes and cooperative annotations. 2) The dataset is collected using a variety of sensors, including vehicle cameras, LiDARs, roadside cameras, and LiDARs.
Real scenario	1) The dataset is collected from the Beijing High-level Automated Driving Demonstration Area, covering 10km urban open roads, 10km urban expressways, and 28 intersections. 2) The dataset covers a wide range of scenarios, including sunny, rainy, and foggy weather conditions, daytime and nighttime driving, urban roads and expressways, and more.

Table 6.2 The Typical Features of DAIR-V2X Dataset

As the pioneer open-source data set for vehicle-infrastructure cooperative autonomous driving in both industry and academia, DAIR-V2X effectively caters to the scientific research, industrial, and government institutions. It actively collaborates with all relevant stakeholders to conduct research on vehicle-infrastructure cooperation, industrial implementation, and municipal planning and construction. This promotes the development of vehicle-infrastructure cooperative autonomous driving, and collectively explores the implementation mode and academic research of vehicle-infrastructure cooperative autonomous driving.

Upon release, this dataset will offer extensive support to explore and implement more vehicle-infrastructure cooperative scenarios in the industrial field. In the academic research field, DAIR-V2X's academic influence and authority have earned recognition from the world's top conference, CVPR. Notably, two papers[44] were produced by AIR, Tsinghua University, and Baidu Vehicle-infrastructure Collaboration Team, based on the dataset's early research work. These papers were presented at the IEEE Conference on Computer Vision and Pattern Recognition in 2022 (CVPR2022).

As of September 2022, DAIR-V2X has been downloaded and utilized by over 3,000 users in China, with a total of over 15,000 data packages downloaded. To further promote the development of vehicle-infrastructure cooperative autonomous driving, AIR in Tsinghua University and Baidu will jointly host the first Vehicle-Infrastructure Collaborative 3D Object Detection Challenge, based on the DAIR-V2X dataset. The challenge aims to fuse vehicle information with infrastructure information to achieve 3D object detection under communication bandwidth constraints, which will attract more researchers from both academia and industry to explore better vehicle-infrastructure cooperative perception technology.

6.1.5 Large-Scale Testing and Operation of L4 Shared Autonomous Vehicles

As of November 14, 2022, Baidu Apollo has conducted road tests in almost 30 cities globally, covering over 40 million kilometers in total. Baidu has secured 718 autonomous driving licenses for testing, of which 571 are for passenger transportation and 194 are for commercial pilot licenses in China. Baidu's autonomous driving travel platform, "Luobo Kuaipao", has launched passenger test operation services in over ten cities, including Beijing, Shanghai, Guangzhou, Shenzhen, and Chongqing, with a fleet of approximately 600 vehicles. Additionally, Baidu has opened the first commercial pilot testing for autonomous driving without a steering wheel in Beijing's Yizhuang area, establishing it as the first unmanned driving life circle in China. Baidu also released full unmanned commercial pilot testing policies in Chongqing and Wuhan and issued the first batch of full unmanned commercial demonstration operation licenses to Baidu.

As of Q3 2022, Luobo Kuaipao has provided over 1.4 million passenger rides to the public, with this number continuing to grow at a rapid pace. Consequently, Baidu has become

44. DAIR-V2X: A Large-Scale Dataset for Vehicle-Infrastructure Cooperative 3D Object Detection. Rope3D: The Roadside Perception Dataset for Autonomous Driving and Monocular 3D Object Detection Task

the world's largest autonomous driving travel service provider. Furthermore, Baidu's Apollo autonomous driving bus has landed in various cities, including Beijing, Guangdong, and Chongqing, with over 370,000 kilometers of cumulative operating mileage and over 260,000 passenger rides for MiniBus and RoboBus.

The Baidu ACE intelligent transportation engine has also been implemented in more than 50 cities, including Beijing, Guangzhou, Changsha, Baoding, Cangzhou, Chengdu, Nanjing, Shanghai, Yangquan, Chongqing, Xi'an, Yinchuan, Hefei, Wuhan, Jinan, Foshan, Haikou, Nantong, Dalian, Hangzhou, Hebi, and Meishan, for practical implementation.

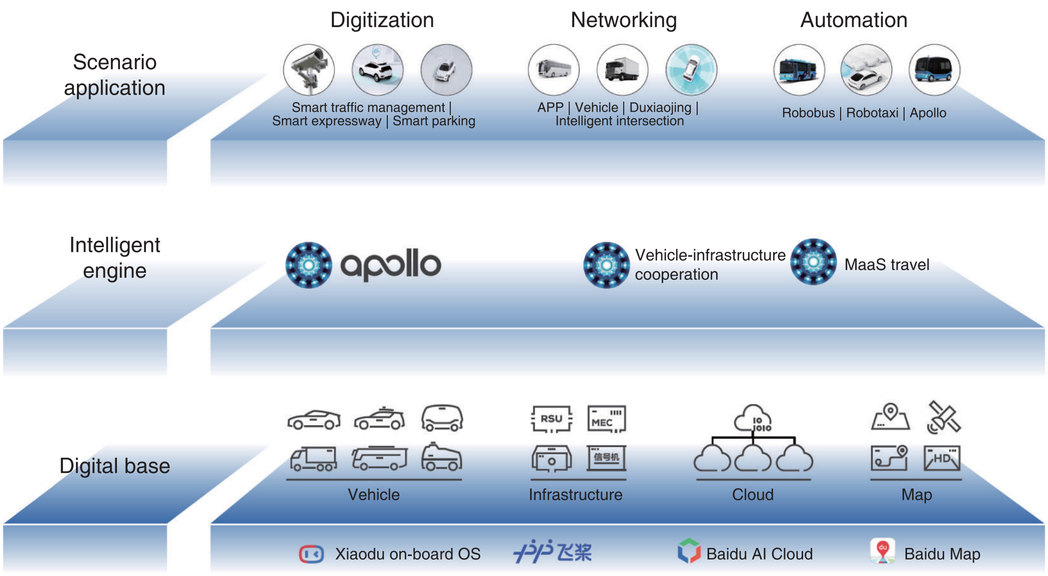


Figure 6.4 ACE Intelligent Transportation Engine 2.0

6.1.6 Services for Clients

(1) Baidu Map (app)

Baidu Map, as a national travel platform and intelligent traffic map digital infrastructure, has applied vehicle-infrastructure cooperation technology to map navigation, creating a "new generation of AI maps". This not only enables billions of users to enjoy the benefits of AI technology but also promotes the intelligent transformation of travel. In some areas such as Beijing Yizhuang, Baidu Map users can receive services such as traffic light countdown, green light start reminder, and lane-level event prompts.

Figure 6.5 Refined Navigation Service Provided by Baidu Map in Yizhuang

(2) Vehicle-mounted intelligent terminal (Duxiaojing)

Baidu has launched Duxiaojing, an intelligent connected rearview mirror terminal, allowing users to receive vehicle-infrastructure cooperation data by installing an intelligent terminal. For example, in Huangpu District, Guangzhou, drivers can enjoy intelligent connected traffic light services such as the traffic light countdown, green light start reminder, red light warning, green light optimal speed reminder, and recommended lanes in the Science City and Knowledge City experience areas.

Figure 6.6 V2X Traffic Light Countdown Service Provided by Duxiaojing

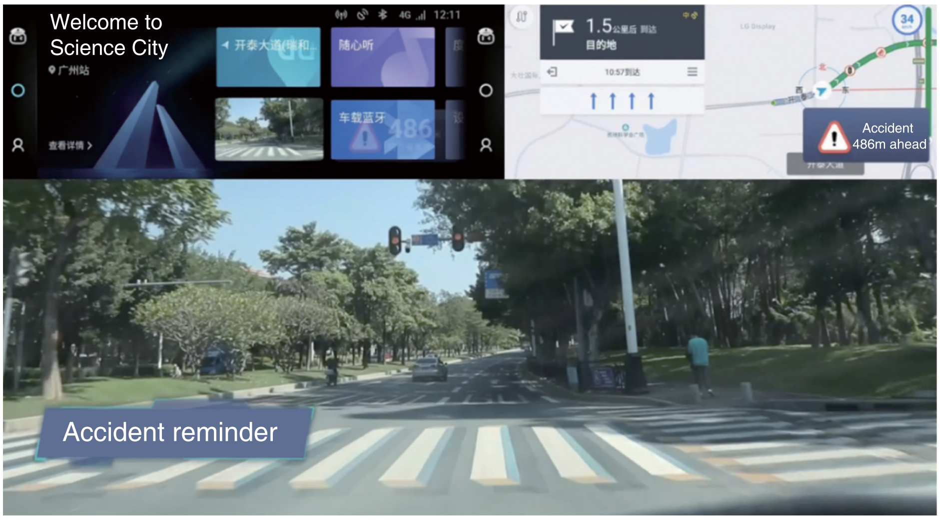


Figure 6.7 V2X Event Reminder Service Provided by Duxiaojing

(3) Intelligent connected vehicles

In addition to serving high-level autonomous vehicles, Baidu's basic service capabilities of vehicle-infrastructure cooperation can be also backward compatible to provide more valuable applications for low-level intelligent connected vehicles. Baidu has established the connected cooperation relationship with 8 OEMs including Ford, providing traffic light warning, green light optimal speed, green light start reminder and other services.

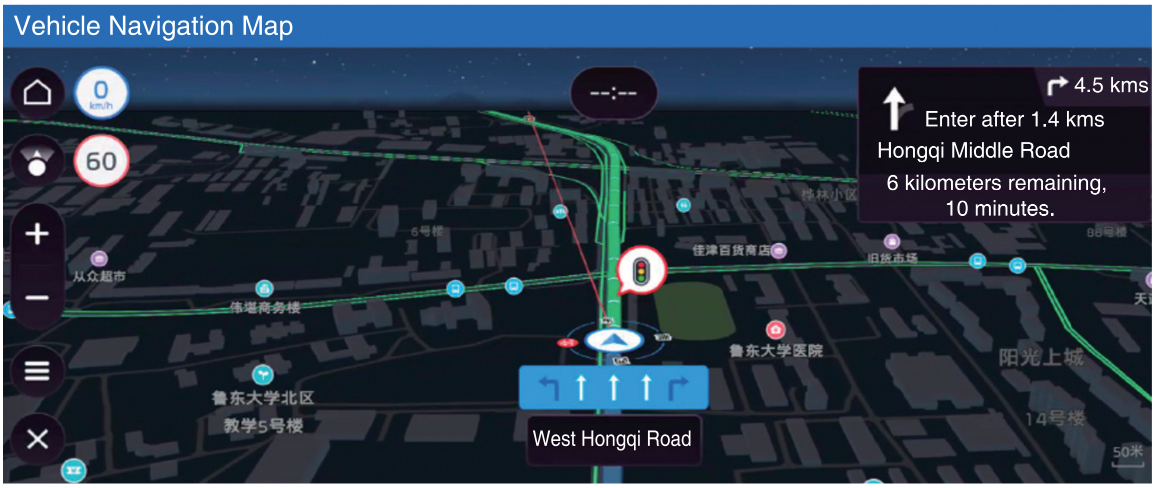


Figure 6.8 Application of Baidu V2X Mass-produced Vehicle

6.2

Typical Practice Scenarios of VICAD

On the basis of fully meeting the industry's published standards, Baidu Apollo has conducted a large number of V2X vehicle-infrastructure cooperative application tests and pilot applications in combination with landed projects. The typical cooperative perception, decision-making and control application scenarios of 19 small categories in 4 large categories are listed in Table 6.3.

Category	Scenario category		Scenario subcategory/name	Applicable standards	Intelligence level of road
1	Real-time update of HD map		Map element change: traffic light	Under establishment	C4
			Map element change: lane line		
2	Collaborative perception		Fusion perception of infrastructure traffic light	YD/T 3978-2021	
			Collaborative perception for static blind spot/occlusion		
			Collaborative perception for dynamic blind spot/occlusion		
			Beyond-visual-range cooperative perception		
			Collaborative perception of low-speed vehicles		
			Collaborative perception of object scattering and low obstacles on road		
			Map element change: lane line		
3	Collaborative decision making and planning	Decision making	Queuing decision making	Under establishment	
			"Malfunctional vehicle" decision making	Under establishment	
		Decision making + Planning	Coordinated passage at an intersection	T/CSAE 157-2020	
			Bypassing congestion	Under establishment	
			Bypassing intersection construction	T/CSAE 157-2020	
		Routing + Decision making + Planning	Cooperative valet parking	T/CSAE 156-2020	
			Formation driving	T/CSAE 157-2020	

4	Collaborative control	Vehicle control: 5G cloud driving	Under establishment	
		Infrastructure control: priority traffic	Under establishment	
		Infrastructure control: green light optimal traffic	Under establishment	

Table 6.3 Examples of Typical Application Scenarios for Baidu Apollo

6.2.1 Real-time HD Map Update Practice

During the implementation of Baidu Apollo, HD maps provide consistent positioning and environmental semantic information for autonomous driving perception, decision-making, planning, and control. HD maps are crucial for autonomous vehicle perception assistance, high-accuracy positioning, safe decision-making and planning.

(I) Map Element Changes - Traffic Signals

Problem description:

In the HD map of automatic driving, traffic signals are one of the important elements of the map. However, the installation position and operating status of traffic signals at intersections often change. If the change information is not synchronized to the vehicle in time, the traffic lights may not be recognized at the intersection, which may cause takeovers or collisions.

a) Intersection traffic light failure, with the temporary traffic light provided

b) The new traffic light at the intersection, with the different location compared to the original

Figure 6.9 Reality Change Scenario of Traffic light at intersection

Scenario principle:

Based on vehicle-infrastructure cooperative perception, V2X communication can be used to update the HD map, assist vehicles in accurately detecting traffic light information in specific areas, and help vehicles safely pass through intersections. The specific logic and process are as follows:

1) Taking a specific intersection as an example, as shown in Figure 6.10, the traffic light is changed from a temporary traffic light installed in the center of the intersection to a horizontal position on the traffic light pole.

2) After detecting the change information at the infrastructure, the new traffic light position will be updated and sent to the map platform. The map compiler can upgrade the HD map through OTA after compilation. When the vehicle passes through the road after the map upgrade, it can obtain the correct position of the traffic light through the map.

3) Before the map version is updated, vehicles passing through the intersection can receive the current latest partial map information sent by the infrastructure through V2X, including the new traffic light position information, as well as the traffic light group, color, and phase information. The vehicle will make driving behavior decisions based on the obtained traffic light position and state information.

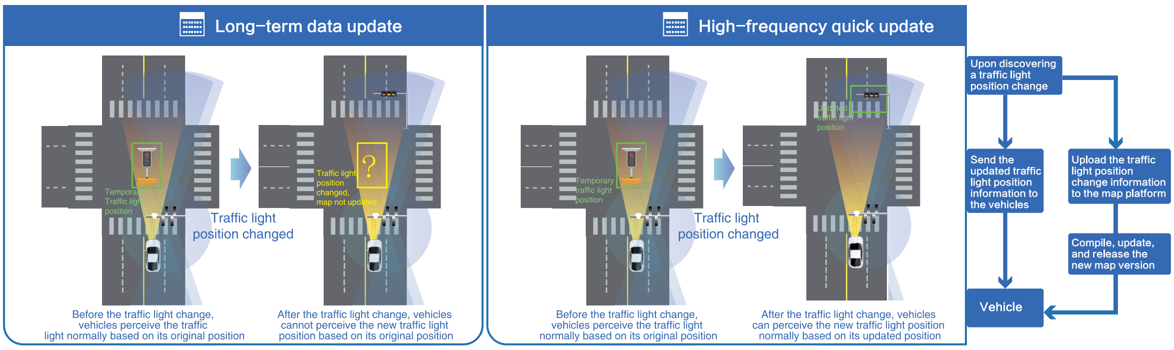


Figure 6.10 Change of Traffic light Position

(II) Map element change - lane line change

Problem description:

As shown in Figure 6.11, due to long-term construction, it is necessary to redraw the lane lines, which may result in complex changes in ground markings such as a reduction in the number of lanes, narrower lanes, and curved lanes. At the same time, there may be situations where the existing lane lines are not cleaned up properly. For autonomous vehicles that rely heavily on high-precision maps, such complex changes in lane features can easily lead to lane perception errors, resulting in dangerous driving behaviors such as not following the directional arrows, driving over lane lines, and crossing into oncoming lanes.

Figure 6.11 Road Lane Line Redrawing Scenario

Scenario principle:

Overall, the Scenario principle involves a coordinated effort between Roadside systems and vehicle-based systems to ensure safe and efficient transportation, with continuous updates to the local map and communication between the vehicle and infrastructure being critical components of this approach.

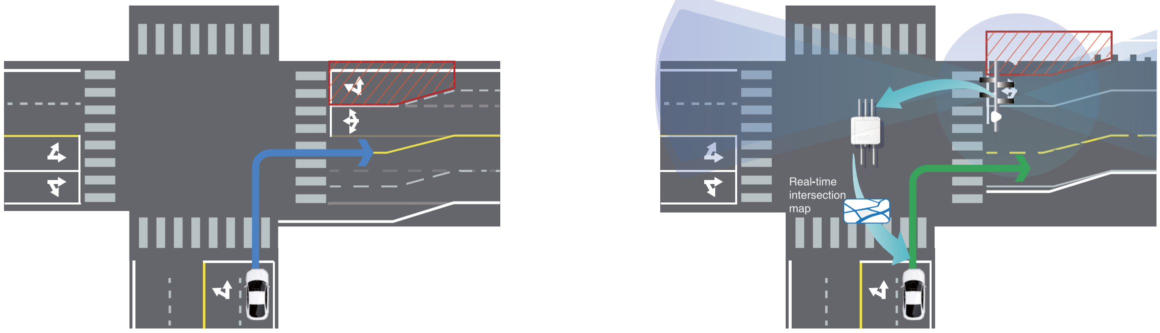
1) Utilize high-frequency fixed-point detection of lane lines at the road-side to promptly detect changes in lane lines and automatically update the lane features of the local map at the road-side. This is accomplished through continuous fixed-point observation, which enables identification of the drivable direction and flow direction of the vehicle, correction of driving direction attributes of the lane, and recording of change information and time of the lane lines.

2) Once the vehicle enters the V2X broadcast range, the current local map of the intersection, including information on lane lines, stop lines, traffic lights, and the confidence level of this information, is broadcasted to the vehicle by the infrastructure.

3) The vehicle then combines its own perception ability with the received data to safely pass through the intersection with lane line changes. (as shown in Figure 6.12).

Update using HD map release

Real-time update of vehicle-infrastructure cooperation map elements at intersection



Due to the failure to update the map in time, the vehicle plans its path according to the lane line in the original HD map, causing that the vehicle drives in the opposite lanev

The latest intersection map is generated through the vehicle-infrastructure cooperation, and the map data is distributed by means of intersection broadcast, so as to guide vehicles into the correct lane

Figure 6.12 Real-time Update of Map Elements at Intersection Through the Vehicle-infrastructure Collaboration Technology

Comprehensive Application Benefits:

The integrated application of updating lane markings and high-precision maps ensures seamless autonomous driving experiences. Following the repainting of lane markings, the updated maps are promptly refreshed. Subsequently, the lane markings are identified and updated at local intersections prior to the arrival of the first vehicle. The system triggers a map version update, enabling the first autonomous vehicle to navigate the intersection smoothly.

6.2.2 Vehicle-Infrastructure Cooperative Perception Practice

(I) Fusion perception of infrastructure traffic light

Problem Description:

The accurate perception of traffic lights is crucial for the safe and efficient operation of autonomous vehicles. However, on the road, the presence of non-standard, multi-semantic, or countdown traffic lights can pose significant challenges for autonomous vehicles. Environmental factors such as obstruction and backlighting, as well as the failure of their own perception ability, can impede the recognition of traffic lights, leading to traffic accidents and decreased traffic efficiency.

Without traffic light cooperative perception, the traffic lights at intersections
is blocked by large vehicles, leading to running red lights or accidents.

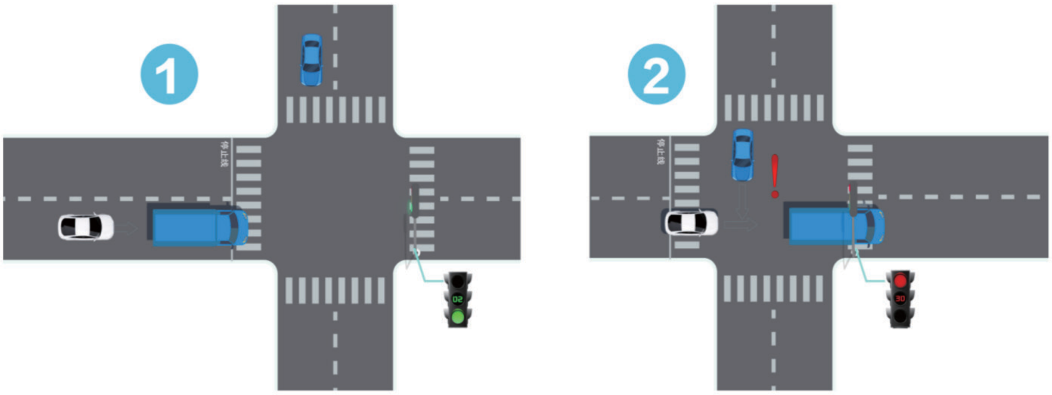


Figure 6.13 Intersection not Supporting Collaborative Perception of Traffic lights

Collaborative perception for beyond-visual-range/ obstructed traffic light:

To overcome these challenges, a cooperative perception approach for super-distance/ obstructed traffic lights is proposed. This approach involves roadside fusion perception, traffic light data access, and cloud traffic light data docking technologies. Through these techniques, real-time traffic light color and countdown information can be obtained from multiple sources of traffic light data. The information is then fused and processed, and sent to autonomous vehicles via V2X communication. This allows vehicles to acquire traffic light information well in advance, enabling them to make informed decisions and controls from a distance, and thus mitigating the risk of traffic accidents.

With traffic light cooperative perception, vehicles can obtain
real-time traffic light data to avoid running red lights or accidents.

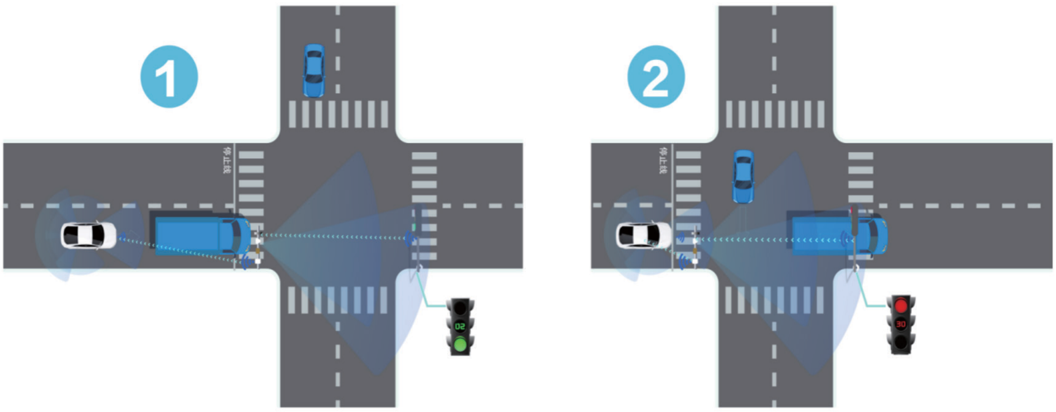


Figure 6.14 Intersection Supporting Collaborative Perception of Traffic lights

Specific case:

A specific case in point involves a scenario where the traffic light is obstructed by a large vehicle ahead, as illustrated in Figure 6.15. In such cases, VICAD traffic light cooperative perception can provide accurate traffic light color and countdown data in real time, facilitating early judgments and decisions by the vehicle's control system to avoid running red lights or emergency braking.

Figure 6.15 Traffic light Blocking Scenario

(II) Collaborative perception for static blind spot/occlusion

Problem Description of AD Blind Spot:
The issue of static blind spots arises due to the limited sensing capabilities of single vehicle sensors. This problem is further exacerbated by dynamic obstacles, such as large vehicles, which can obstruct the view of the vehicle and make it challenging to accurately perceive the movement of vehicles or pedestrians in the blind spot.

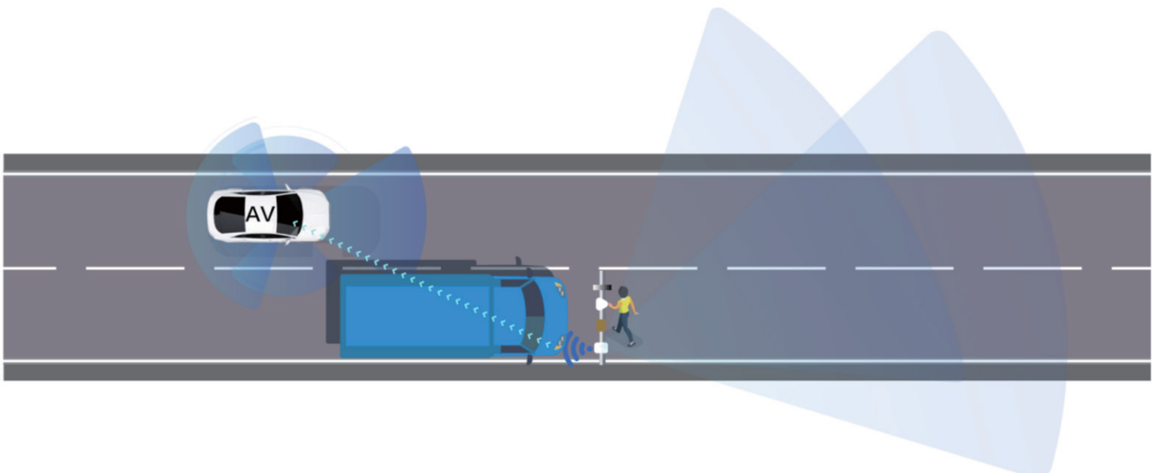


Figure 6.16 Static Blind Spot: Sudden Pedestrian Intrusion

VICAD-based cooperative perception for dynamic and static blind spot:

As shown in Figure 6.17, VICAD Dynamic and Static Blind Spot Cooperative Perception involves the deployment of multiple sensors along the roadside to enable continuous detection and recognition in multiple directions and over long distances. By fusing these sensor data with the vehicle perception system, the autonomous driving vehicle can accurately perceive and recognize the presence of vehicles or pedestrians in the blind spot. This enables the vehicle to make timely decisions, leading to reduced accident risks.

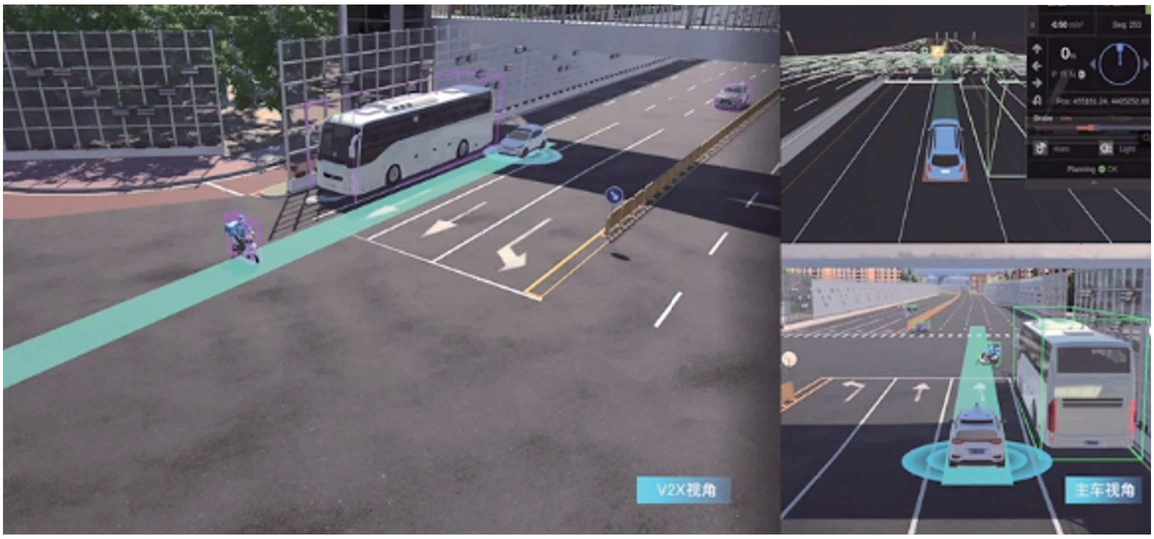


Figure 6.17 Collaborative Perception of Non-motorized Vehicle/Pedestrian 'Blind Zone' in Static Blind Spots

(III) Collaborative perception for dynamic blind spot/occlusion

(1) Collaborative perception for Left-Turn/U-Turn Blind Spot or Occlusion:

As depicted in Figure 6.18, a vehicle making a left turn or a U-turn at an intersection may experience a dynamic blind spot or occlusion due to the presence of a large truck or bus (indicated by a pink polygon), which obstructs the view of the vehicles following behind. Leveraging the capabilities of VICAD full-collaborative perception, the vehicle can acquire the motion information of the obstructed vehicle and mitigate the potential risk of sudden braking or accidents.

Figure 6.18 Collaborative perception for Left-turn/U-turn Blind Spot or Occlusion

(2) Collaborative perception for large vehicle occlusion:

When a vehicle is driving straight, a large vehicle on the left obscures an electric bicycle crossing the road. Through VICAD dynamic and static blind spot collaborative perception, the vehicle can obtain the motion information of occluded vehicles, non-motorized vehicles, or pedestrians in advance, avoiding the risk of sudden braking or accidents (as shown in Figures 6.19 and 6.20).

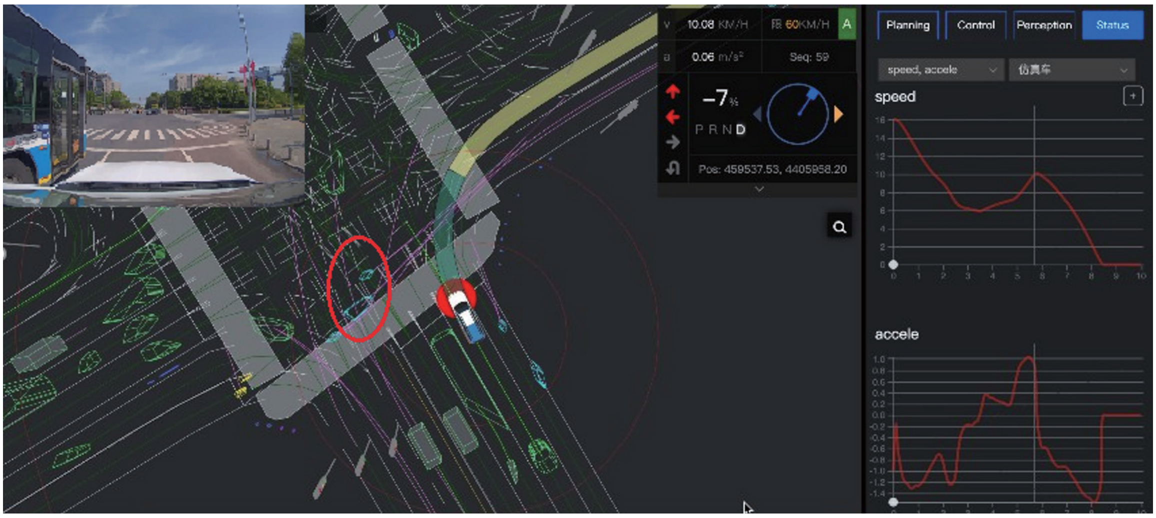


Figure 6.19 Large Vehicle Occlusion Scenario at Intersections

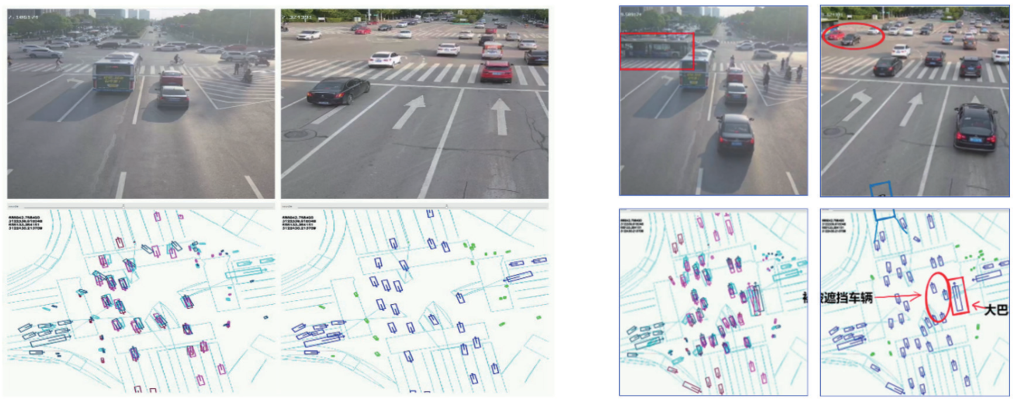


Figure 6.20 Vehicle-infrastructure Collaborative Perception for Large Vehicle Occlusion at Intersections

(IV) Beyond-visual-range cooperative perception

Problem Description of AD beyond-visual-range perception:

The effectiveness of on-board sensors in vehicles is limited by their type, sensing range, and resolution, which leads to unstable perception of traffic conditions, traffic participants, or obstacle detection results beyond the coverage of on-board sensors. This can result in problems such as perception loss or abrupt changes in perception.

VICAD-based beyond-visual-range cooperative perception:

To overcome the limitations of on-board sensors, multiple sensors are deployed on the roadside as shown in Figure 6.21. These sensors achieve multi-directional, long-distance continuous detection and recognition, which is then fused with vehicle perception to achieve accurate perception and recognition of vehicles or pedestrians beyond-visual-range for autonomous driving vehicles. This allows vehicles to make decisions in advance and reduce the risk of accidents.

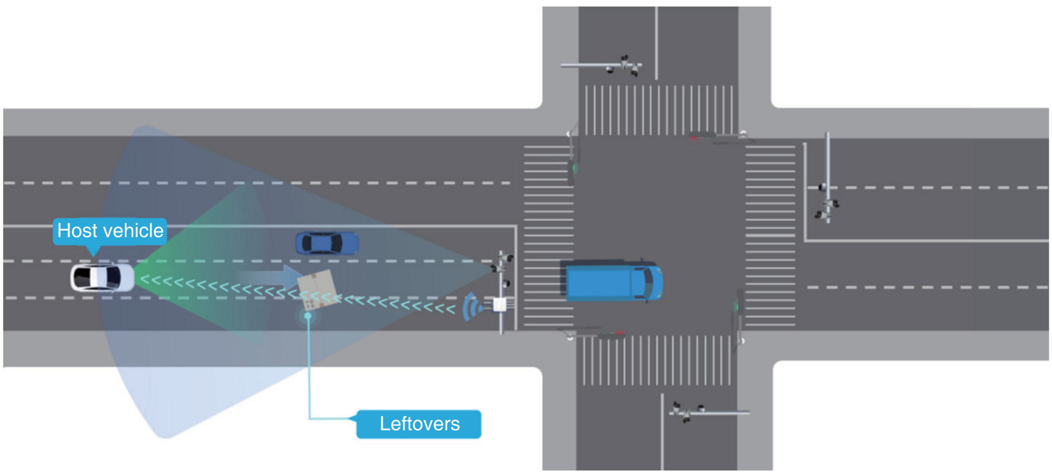


Figure 6.21 Beyond-visual-range Collaborative Perception

Specific case:

Figures 6.22 and 6.23 show the detection and fusion results of both vehicle and infrastructure at the same time. In Figure 6.22, the vehicle (blue and white) experiences difficulty in stably detecting obstacles in the far distance, as evidenced by the lack of obstacle detection along the driving path. This can lead to sudden braking and accident risks. In contrast, Figure 6.23 shows that VICAD-based Beyond-Visual-Range Cooperative Perception enables the vehicle to obtain motion information of the front vehicle, non-motorized vehicle, or pedestrian in advance, as indicated by the pink box near the path. This allows the vehicle to avoid sudden braking or accident risks.

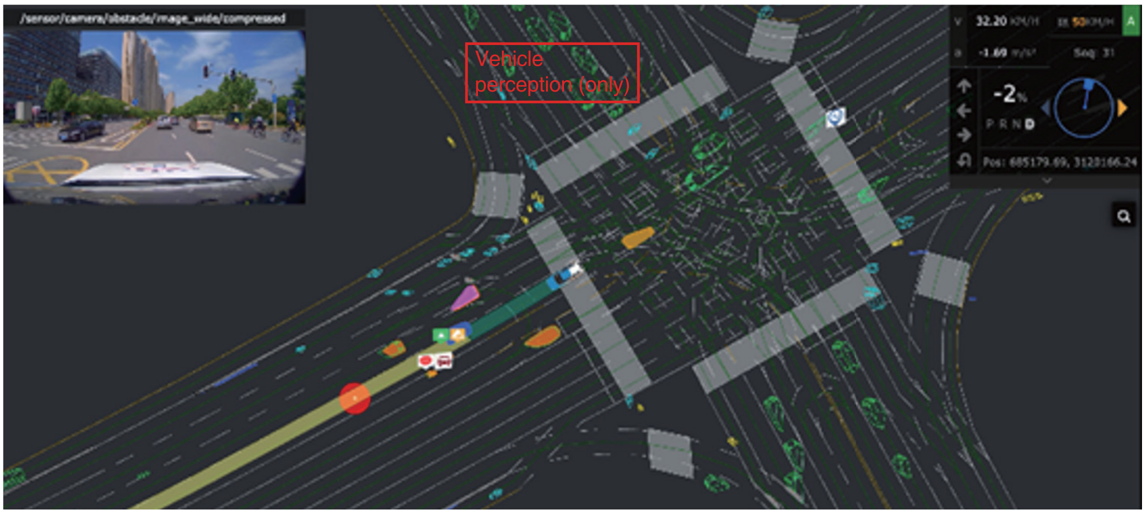


Figure 6.22 Vehicle perception (only)

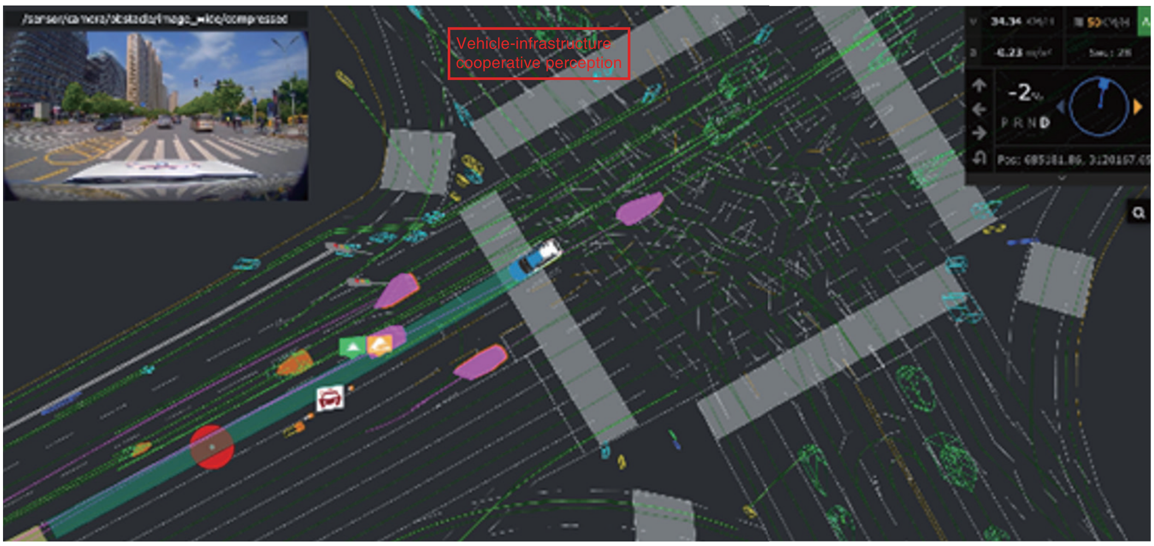


Figure 6.23 Vehicle-infrastructure cooperative perception

(V) Cooperative Perception of Low-Speed Vehicles

Description of AD low-speed vehicle perception problem:

One of the challenges in autonomous driving (AD) is the accurate detection of low-speed vehicles on the roadside due to various factors such as the sensing angle of the vehicle-side sensor and real-time vehicle movement. This inaccuracy can lead to potential collisions or emergency braking risks, particularly when low-speed vehicles are reversing or driving out from the roadside.

VICAD-based cooperative perception of low-speed vehicles:

As shown in Figure 6.24, VICAD-based system achieves continuous detection and recognition of the road in multiple directions and at long distances, which is then integrated with vehicle perception to improve the accuracy of low-speed vehicle or pedestrian detection for autonomous driving vehicles. By enabling the vehicle to make decisions in advance, the system effectively reduces accident risks.

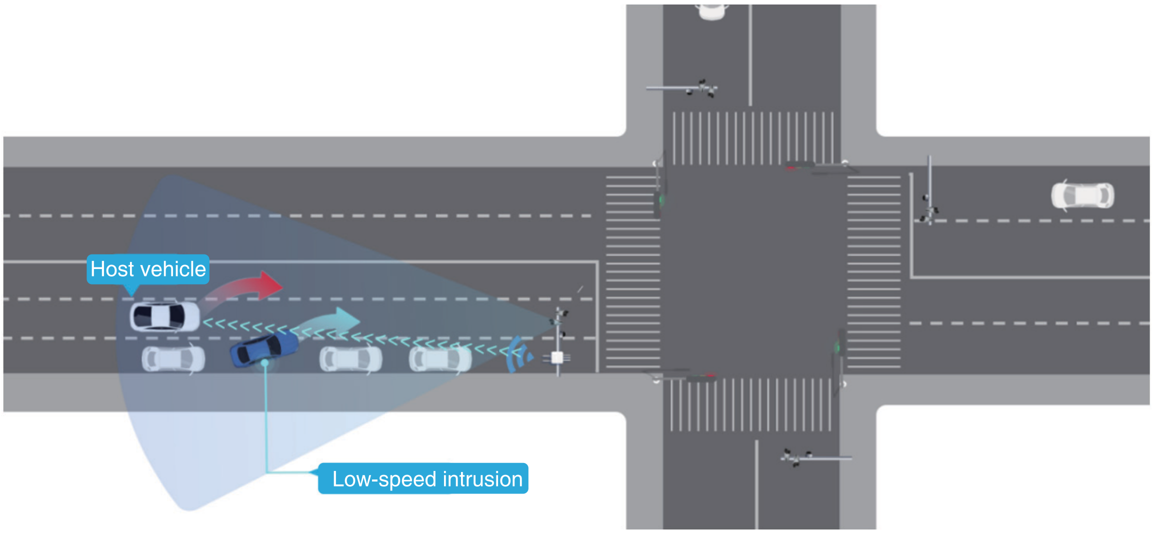


Figure 6.24 Collaborative Perception of Low-speed Roadside Vehicles

Specific case:

For instance, in the case of a vehicle traveling straight with VICAD cooperative perception, low-speed vehicles driving out from the roadside can be stably detected, and accurate information such as vehicle speed and position can be obtained and sent to the vehicle for fusion perception and positioning. This approach effectively avoids emergency braking or accident risks. (Figure 6.25).

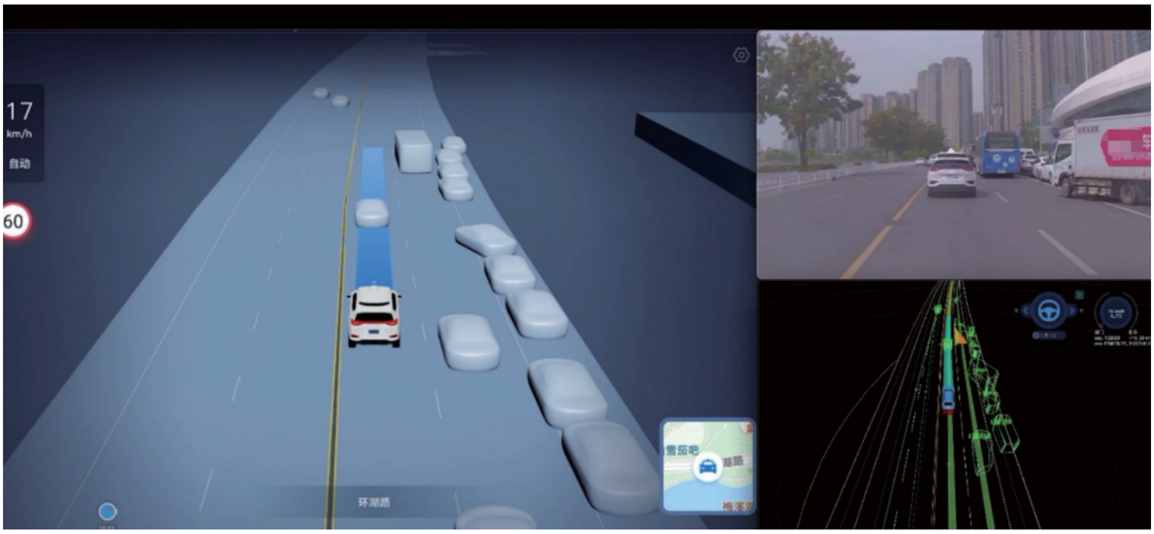


Figure 6.25 Collaborative Perception of Low-speed Roadside Vehicles

(VI) Collaborative Perception for Low Obstacles

Problem description:

The capability to perceive low obstacles is critical for autonomous driving systems, requiring a high success rate in detecting obstacles no smaller than 5 centimeters with a success rate of no less than 99%. However, the success rate of L4 vehicle detection is generally not achievable, and detecting low obstacles in front of the vehicle is challenging. This can lead to potential missed or false detections, resulting in sudden braking or accidents.

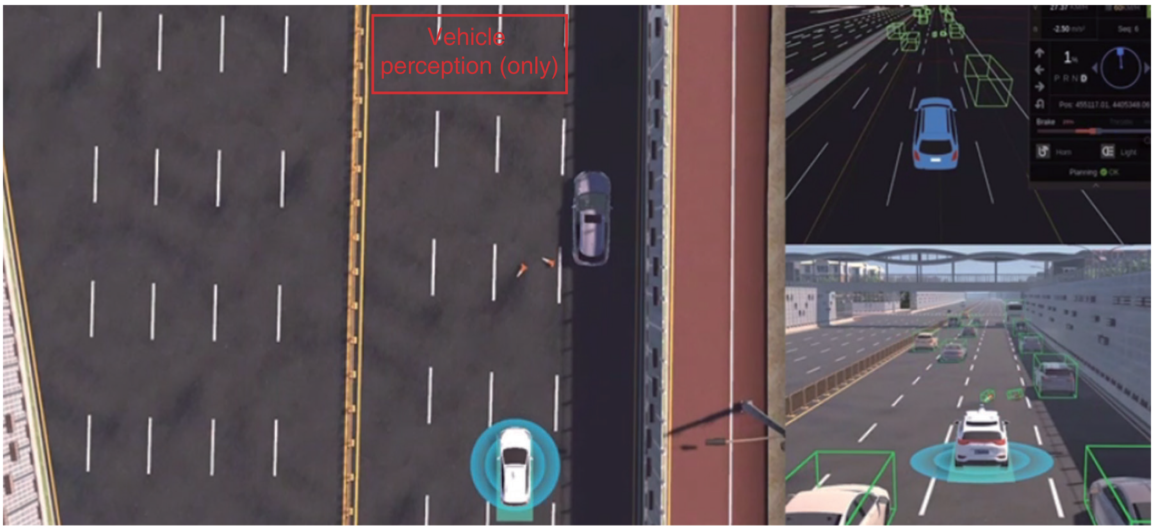


Figure 6.26 Vehicle Perception only: Failure to Accurately Identify Object Scattering Scenario at a Long Distance

Scenario principle:

To address this challenge, the scene employs a vehicle- infrastructure cooperative perception approach to achieve continuous and stable detection and recognition of low obstacles. Since the roadside sensing devices infrastructure perception equipment are fixedly installed, they can leverage background modeling data, both real-time and historical, to achieve higher detection rates and more accurate perception of low obstacles. The perception system can then send obstacle information to the vehicle in advance, enabling safer driving decisions such as lane changing or slowing down (as shown in Figure 6.27).

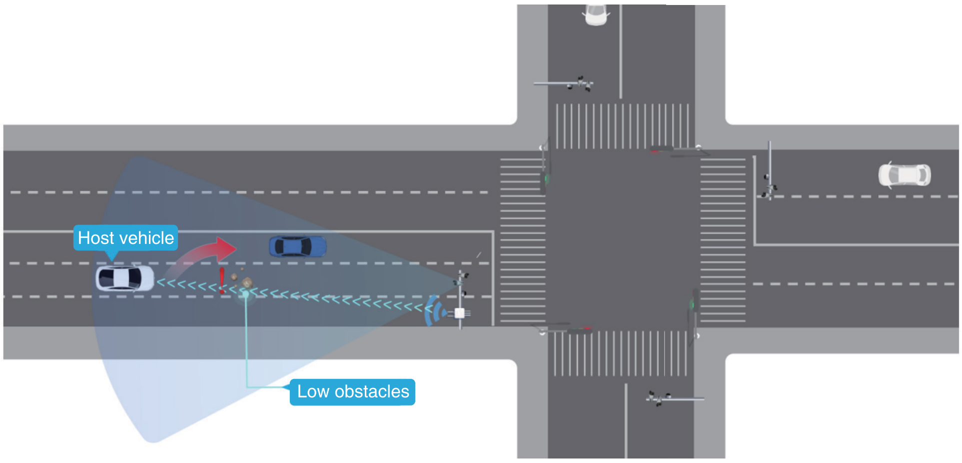


Figure 6.27 Collaborative Perception of Low Obstacles

Application Benefits:

With the infrastructure system, low obstacles such as leftovers on the road can be effectively detected, and then the information is transmitted to the vehicle via V2X communication for early decision-making (as shown in Figure 6.28).

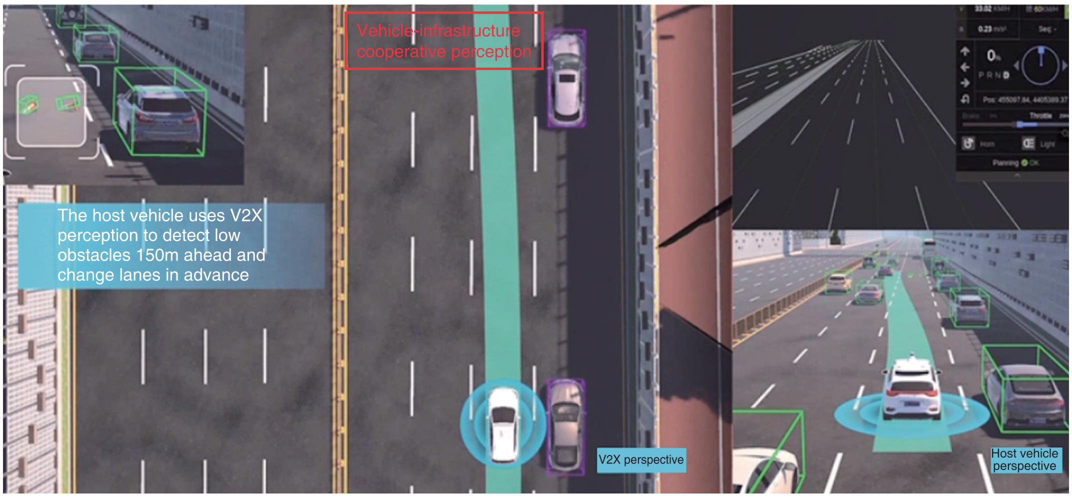


Figure 6.28 Recognition of Object Scattering on Road With VICAD Collaborative Perception

6.2.3 Vehicle-Infrastructure Cooperative Decision-Making and Planning Practice

(I) Decision-making in Queueing Scenarios:

Problem Description:

In a queueing scenario, autonomous vehicles are in a following state and the traffic light at the intersection ahead is red, causing a queue of vehicles going straight. At this time, the vehicle cannot judge the reason why the front vehicle stops (in the queue) and may choose to overtake to the left (turning lane) and change lanes (as shown in Figure 6.29). However, when approaching the intersection, due to too many queued vehicles in the lane, the vehicle may not be able to change lanes back to the original lane, causing traffic congestion.

Figure 6.29 Queuing Scenario

Scenario principle:

Through VICAD, the traffic event is perceived in a timely manner, and the queueing event is promptly sent to the vehicle. To avoid the vehicle from erroneously turning left and unable to change lanes back to the original lane, the decision to wait in the lane for queuing is given to the vehicle (as shown in Figure 6.30).

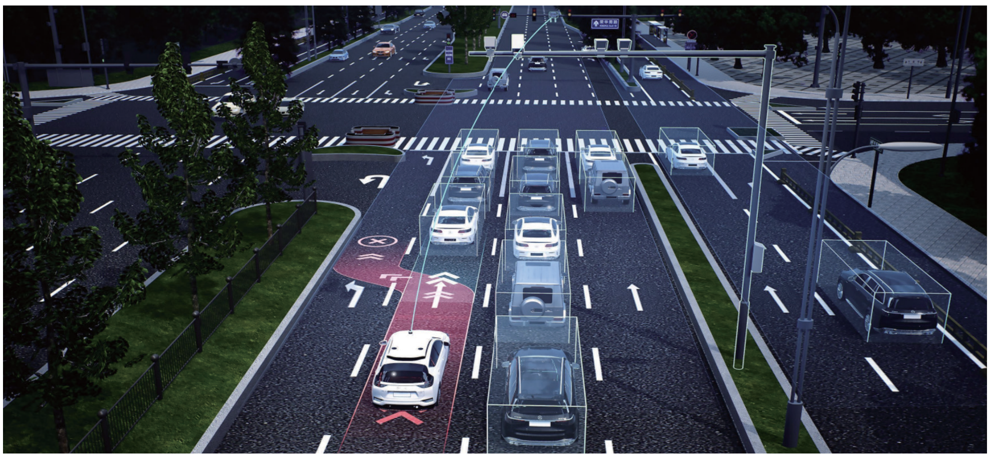


Figure 6.30 Decision-Making in Vehicle Queuing Scenarios

(II) Decision-Making in " Malfunctional Vehicle" Scenarios

Problem description:

In the context of Intelligent Transportation Systems (ITS), the " malfunctional vehicle" scenario refers to a situation where a large vehicle occupies two lanes, obstructing the road ahead and causing approaching vehicles to stall due to the lack of visibility and information about the road ahead (as depicted in Figure 6.31).

Figure 6.31 "Malfunctional Vehicle" Scenario

Scenario principle:

VICAD facilitates the tracking and prediction of road vehicles over an extended period, thus allowing timely dissemination of information about the " malfunctional vehicle" scenario to nearby vehicles. The VICAD system provides drivers with the necessary information to make decisions promptly such as changing lanes to avoid stalling (as illustrated in Figure 6.32).

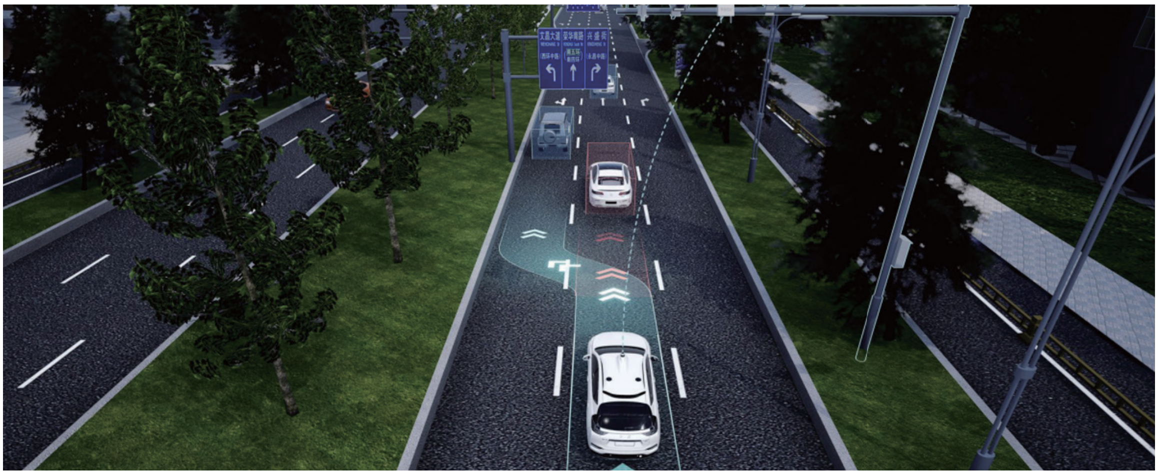


Figure 6.32 Decision-Making in " Malfunctional Vehicle" Scenarios

(III) Coordinated Passage at Intersections

Problem description:

As shown in Figure 6.33, the autonomous vehicle is currently in operation within a straight lane. Concurrently, another vehicle approaching from a bifurcation point, such as a crossroad or diverging and merging area, is intending to execute a left turn and merge into the aforementioned lane. This maneuver results in a conflict with the autonomous vehicle's trajectory. In the absence of coordinated protocols, the host vehicle may be forced to engage in emergency braking or undergo a takeover operation.

Figure 6.33 Intersection Conflict Scenario (Without Vehicle-infrastructure Collaborative Decision-making)

Scenario principle:

1) Through vehicle-infrastructure cooperation, both the vehicle and the infrastructure report the vehicle intention (expected trajectory, including the vehicle position and speed at each moment) through V2X communication;

2) The infrastructure or cloud system arbitrates the passing strategy for the host vehicle and the merging vehicle based on the vehicle intention, traffic rules (yielding to driving-straight vehicles when turning left), and vehicle status information. The strategy prioritizes driving-straight vehicles, allowing them to pass efficiently while left-turning vehicles slow down and follow;

3) Both vehicles execute the arbitration results and efficiently pass the intersection without stalling.

Application Benefits:

As shown in Figure 6.34, through the integrated cooperation of vehicle-infrastructure-cloud decision-making, reasonable arbitration of vehicle passing sequence is achieved, ensuring that driving-straight and left-turning merging vehicles pass through in an orderly and efficient manner, avoiding traffic congestion or collision risks caused by interaction conflicts, and improving traffic efficiency and safety.

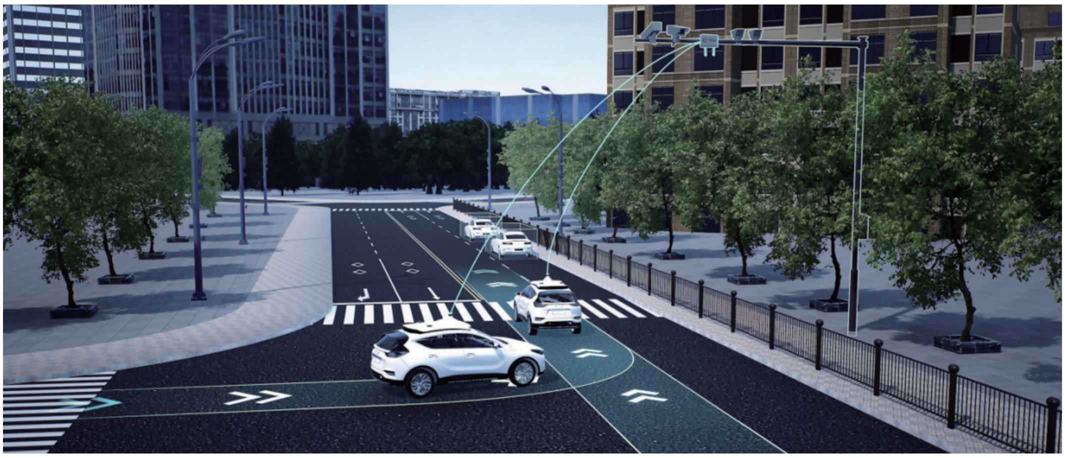


Figure 6.34 Coordinated Passage Under Intersection Conflict Scenario (With Vehicle-infrastructure Collaborative Decision-making)

(IV) Detouring around Blockings

Problem description:

Autonomous vehicles face challenges when navigating through construction events that block the lane while driving in a straight path (as depicted in Figure 6.35). The complexity of such situations makes it difficult for the vehicle's autonomous system to discern the driving intentions of the leading vehicle and determine the optimal queuing or detour strategy, leading to suboptimal vehicle congestion or detours.

Figure 6.35 Traffic Blocked by Construction

Scenario principle:

1) The infrastructure offers the advantage of long-term observation and scene understanding, which can be combined with multi-source data input from the cloud to determine the type of blocking scene ahead and the vehicle's state attributes.

2) In instances where the main vehicle's lane is blocked due to construction, abnormal vehicle parking (e.g., vehicle failure, illegal parking, etc.), and an adjacent lane is available for detouring, the system provides advice on the optimal detour strategy to avoid congestion.

Application Benefits:

As shown in Figure 6.36, VICAD offers a solution for autonomous vehicles to navigate through blocking scenario seamlessly.

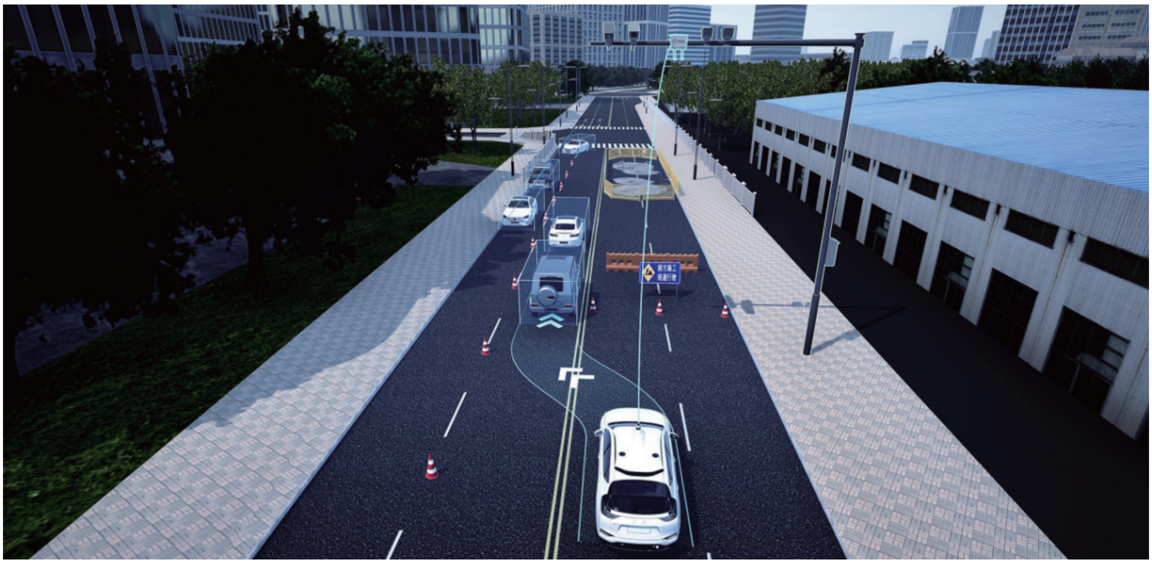


Figure 6.36 Detouring and Crossing Solid Yellow Line in Case of Road-occupied Construction

(V) Detouring around Construction Area at Intersections.

Problem description:

As shown in Figure 6.37, autonomous vehicles may encounter obstruction events, such as construction zones or vehicles stopped abnormally, when driving into road areas without lane markings, such as the central area of an intersection, which may require them to re-plan their driving trajectory to detour around the obstruction. The complexity of the obstruction event and the absence of lane information in such road areas may make it difficult for the autonomous vehicle to execute a detour decision, resulting in unreasonable stops.

Figure 6.37 Construction at Intersections

Scenario principle:

1) The infrastructure leverages its long-term observation advantages to obtain information on the type, range, distribution, and surrounding traffic conditions of the obstruction area;

2) Based on historical traffic trajectory data around the obstruction area, the infrastructure or cloud system selects the optimal passing strategy and generates a recommended trajectory guide line and speed suggestion applicable to the autonomous vehicle, which is then transmitted to the vehicle.

3) The autonomous vehicle can then follow the trajectory guide line issued by the roadside/cloud system to detour the obstruction area, as shown in Figure 6.38.

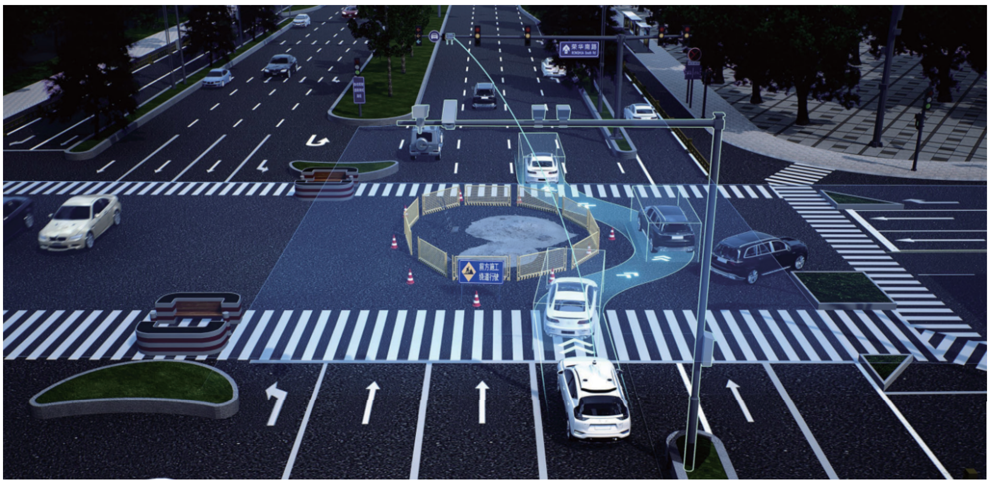


Figure 6.38 Scenario of Detouring around Construction Area at Intersections

Application Benefits:

It enables autonomous vehicles to smoothly detour around road obstruction areas at intersections, thus improving their efficiency and reducing traffic congestion.

(VI) Cooperative Valet Parking

Problem Description:

Whether it is an L2 or L4 vehicle, there may be safety hazards when facing parking scenarios due to complex parking lot environments, lack of positioning signals, etc. In addition, it takes a lot of time to find available parking spaces, resulting in low efficiency and even long queues.

Scenario principle:

1) Achieve comprehensive coverage of cooperative parking cruise roads and exclusive parking spaces in the parking lot, detect vehicles, pedestrians, obstacles, and other targets in the parking lot, and monitor the occupancy status of parking spaces in real-time;

2) When a human or vehicle actively applies for cooperative parking, the cloud combines perception data from the vehicle and parking lot to conduct global scheduling and provide a global navigation route to support the vehicle to go to the nearest empty parking space;

3) After the vehicle receives the scheduling information, it enters a low-speed autonomous driving state, which can combine the actual situation of the parking lot to achieve low-speed autonomous driving in the parking lot, including: straight road cruising, curve cruising, intersection passing, uphill and downhill, speed bump passing, low-speed following, fixed scene obstacle avoidance, and fixed-point parking;

4) When there is a blind spot in the parking lot, the parking lot's intelligent terminal will transmit the calculation results to the vehicle side, and the vehicle can actively slow down to avoid collisions.

Application Benefits:

Cooperative valet parking can help vehicles quickly find parking spaces and achieve automatic driving in and out of parking spaces without driver involvement. Figures 6.39-41 respectively show the construction of Baidu AVP valet parking in Yizhuang, Beijing.

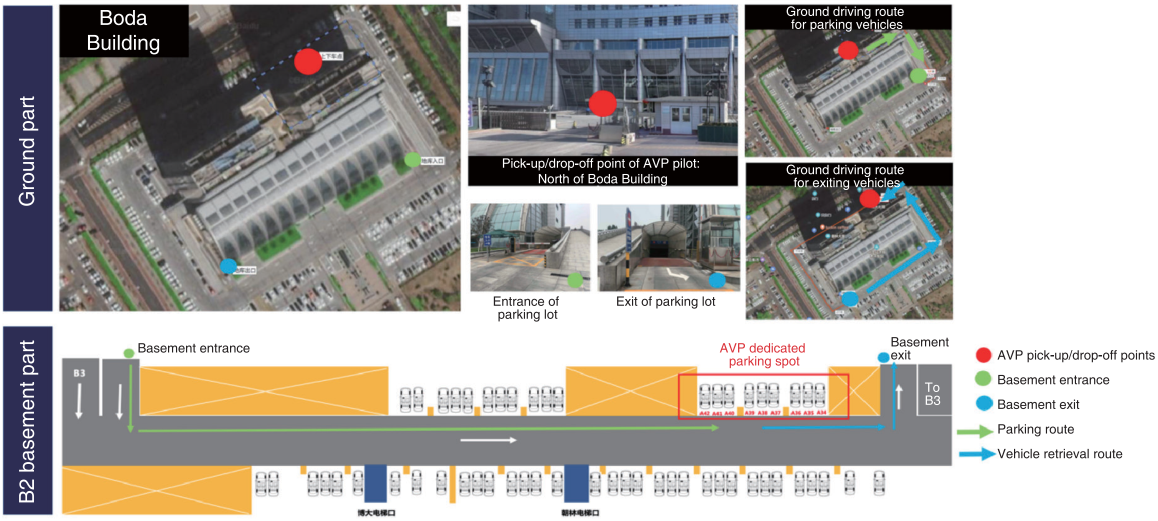


Figure 6.39 AVP Parking Lot Route of Beijing Yizhuang Administration Committe

Figure 6.40 Ground & Underground AVP Dedicated Parking Spaces of Yizhuang Administration Committee in Beijing

Figure 6.41 AVP intelligent kit.

(VII) Formation driving

Problem description:

In the scenario of autonomous formation driving, the formation is composed of a leading vehicle and member vehicles. The leading vehicle initiates or dissolves the formation according to the cloud control command, while the member vehicles decide whether to join or leave the formation.

Scenario principle:

1) Formation Initiation: Before forming a formation, the leading vehicle confirms the request to initiate the formation and broadcasts real-time information such as its destination, formation ID, formation speed, and following distance to all surrounding vehicles. After the surrounding vehicles confirm to join the formation, they re-plan their paths based on the position and distance information of the following object, calculate and control the speed to merge into the formation. After joining the formation, they maintain a consistent driving state in accordance with the unified recommended planning information of the formation (recommended speed, recommended distance, recommended lane);

2) Formation Dissolution: The leading vehicle of the formation receives the dissolution message from the cloud and broadcasts the dissolution request to the formation vehicles. The member vehicles automatically leave the formation and re-plan their paths to the original destination after leaving the formation.

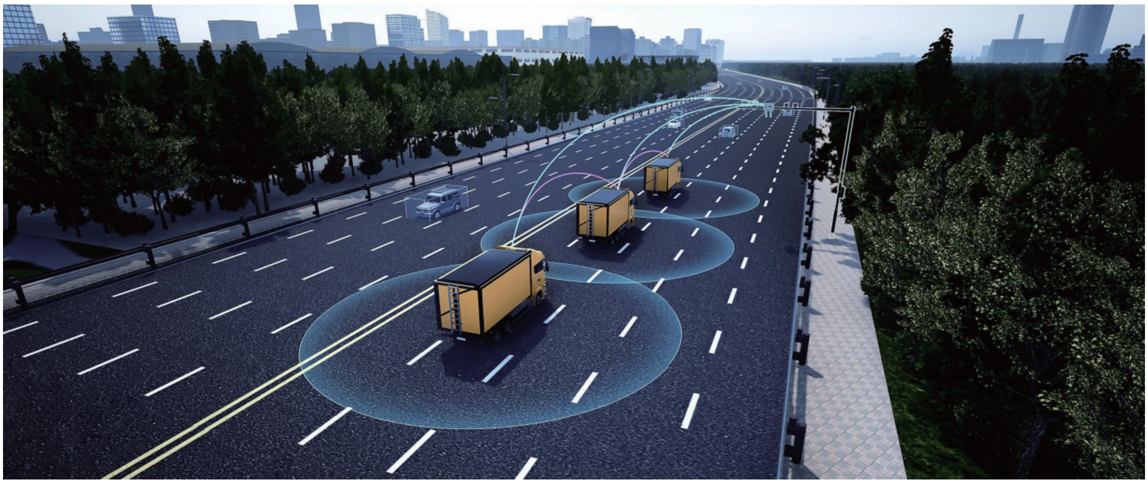


Figure 6.42 Formation Driving Scenario

Application Benefits:

In the context of the Nanchang-Jiujiang Expressway project, Baidu and its collaborators collaborated in the implementation of formation vehicle driving, thereby conducting comprehensive tests on both single-vehicle and formation-based driving capabilities. This testing effectively demonstrated the autonomous driving formation capability at a speed of 60km/h and achieved the successful deployment of applications such as 3-vehicle formations, as well as effective following, deceleration, acceleration, and dissolution of the formation.

6.2.4 Vehicle-Infrastructure Cooperative Control Practice

6.2.4.1 Vehicle control: “5G Cloud Driving”

Autonomous vehicles encounter unique situations during their operation, such as temporary road changes or traffic control. The emergence of 5G technology provides a platform for high-bandwidth, low-latency, and highly stable data connections, enabling remote drivers to control vehicles via a "5G Cloud Driving" console. This console enables drivers to manage vehicle operations remotely, including controlling the steering wheel and pedals, and addressing vehicle issues as they arise. This approach reduces operating costs by allowing one cloud driver to serve multiple vehicles at the same time, given the infrequency of extreme scenarios requiring "5G Cloud Driving" intervention.
Numerous cities in China, including Beijing, Shanghai, Guangzhou, and Chengdu, have implemented "5G Cloud Driving." On April 28, 2022, Beijing became the first city to allow autonomous vehicles to operate without a human driver behind the wheel. Additionally, on November 21, Beijing issued a notice for the unmanned operation of autonomous vehicles, with Baidu becoming the first company to be granted permission for unmanned vehicles testing. The utilization of "5G Cloud Driving" ensures the safety of autonomous driving, enhances passenger safety, and ultimately improves the riding experience.

Figure 6.43 "5G Cloud Driving" Robotaxi Application

"5G Cloud Driving" can be effectively implemented in diverse contexts, including parking facilities, low-speed unmanned vehicles, ports, mining operations, and specialized missions. For instance, in the mining industry, "5G Cloud Driving" technology can facilitate automated mining activities such as loading, transporting, and unloading materials within the mining site. This includes queuing in the loading and unloading zones, automated loading and unloading procedures, transportation of full and empty loads, and the removal of soil from the mine's edges. Such applications can generate significant cost savings, amounting to over 1 million yuan annually, for each vehicle involved in the mining operations.

Figure 6.44 "5G Cloud Driver" Intelligent Mining Application

6.2.4.2 Controlling Infrastructure

(I) Priority Passages for Single-Point Control Traffic lights

In actual traffic operation environments, special vehicles (accident rescue, medical assistance, security protection) often perform special tasks and require certain priority passage rights to save time for these vehicles. At the same time, buses and coaches, which have the characteristics of public transportation, can also be granted certain priority passage rights from the perspectives of energy saving, emission reduction, and traffic efficiency, to avoid traffic congestion.

Problem Description:

To respond to the emergency travel tasks of special vehicles, such as medical treatment and fire protection, there is an urgent need to open the "green life rescue passage". Currently, during the passage of special vehicles, there are difficulties such as social vehicles unable to perceive and yield in advance, safety hazards at intersections due to scrambling, and inability to achieve global precise allocation through manual operation. A common approach is to set up dedicated traffic lights for priority passage vehicles on the road, as shown in Figure 6.45. This approach requires additional traffic lights to be installed on the signal pole, leading to too many roadside devices.

Figure 6.45 Bus-specific traffic light

Scenario principle:

The overall principle of vehicle priority passage based on vehicle-road coordination is as follows:

1) Special vehicles submit priority passage applications to the platform through navigation before departure, and the platform will develop an optimal path and real-time navigation service for the vehicles;

2) Vehicles report their location information to the platform in real-time (or the infrastructure detects and identifies the vehicles in real-time), and the platform optimizes or controls the navigation of the vehicles in the lanes ahead of them, giving way to special vehicles;

3) When special vehicles approach the intersection, the infrastructure optimizes and controls the signal phase of the lane where the vehicles are located (such as extending the green light), giving priority passage rights to special vehicles.

Application Benefits:

Taking a certain project in Beijing Yizhuang as an example, VICAD provides the necessary "green passage" for special vehicles, as shown in Figure 6.46. Vehicles achieve relatively priority travel without running red lights and minimizing the disturbance on traffic order, thereby fully guaranteeing overall traffic efficiency.

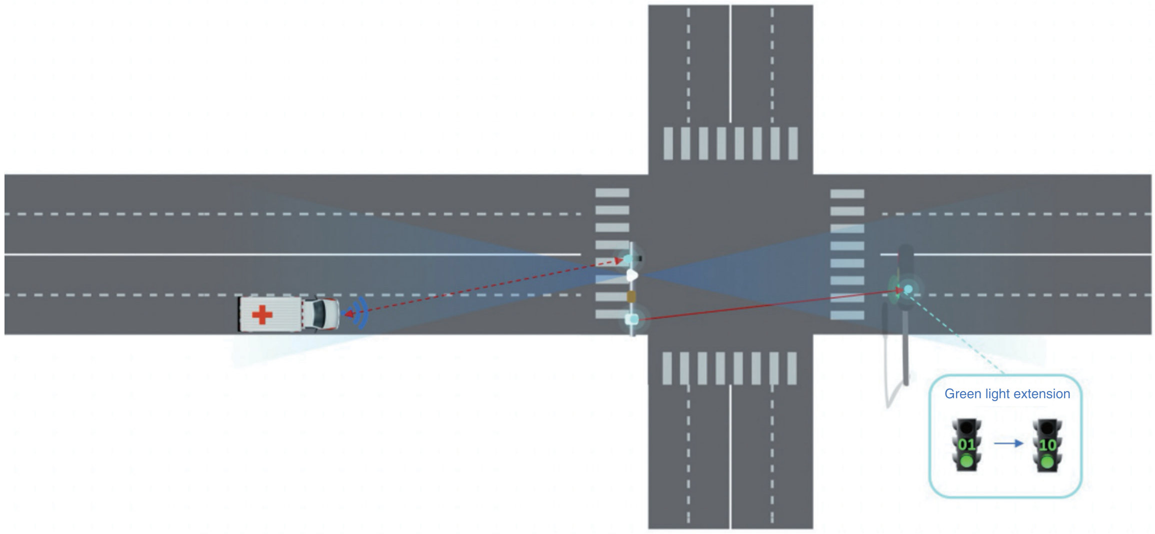


Figure 6.46 Application Benefits of Priority Passage for Special Vehicles

(II) Main Road/Regional Green Wave Signal Control、

Problem description:

Vehicles often have to wait at intersections due to red lights, which reduces the overall traffic speed and efficiency.

Scenario principle:

Vehicle-infrastructure cooperation system monitors, predicts, and analyzes the overall traffic situation. By combining factors such as the vehicle's location, signal control cycle, and traffic regulations, personalized traffic recommendations (such as recommended vehicle speed) are provided to allow vehicles to pass through multiple intersections continuously with green lights, reducing the probability of traffic congestion.

Scenario process:

The specific implementation steps of this scenario are as follows:

1) Collect traffic flow, delay time, average speed, and other traffic indicators data on the road for a period of time;

2) Based on the analysis of traffic indicator data, optimize the traffic light cycle from the perspective of control infrastructure, and design the theoretical vehicle speed passing through the green wave on the main road;

3) Send the recommended vehicle speed to the vehicle. Based on its position and operating status, the vehicle can develop a more reasonable driving speed

4) Vehicles pass through the intersection with continuous green lights according to decision-making and control instructions, improving travel efficiency.

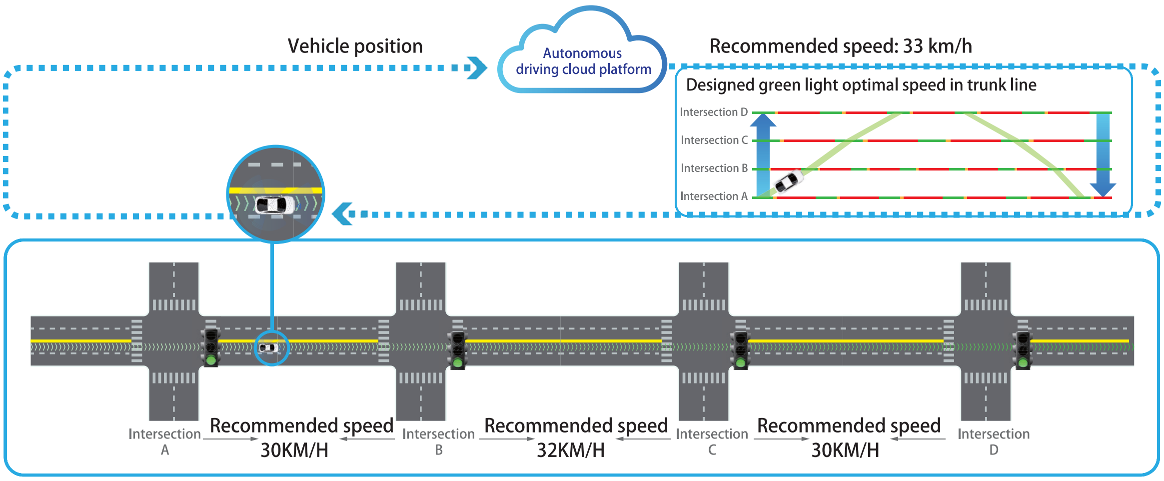


Figure 6.47 Vehicle Speed Guidance

Application Benefits:

Based on the actual traffic flow data of various intersections in Beijing Yizhuang, adaptive control methods and GNN-based data prediction and completion methods (see Figure 6.48 for details) were used to optimize and control the regional traffic lights, and the performance comparison is shown in Table 6.4. All-day delay represents the average delay from 0:00 to 24:00; morning peak delay represents the average delay from 7:00 to 9:00; off-peak delay represents the average delay from 10:00 to 16:00. The results show that the GNN-based data prediction and completion method can effectively improve traffic efficiency and reduce vehicle delay various different time periods.

Evaluation indicators	Adaptive control	GNN prediction + holographic intersection solution	Enhancement effect
All-day delay (s)	26.31	24.68	6.21%
Morning peak delay (s)	40.46	34.43	14.91%
Off-peak delay (s)	15.04	13.70	8.93%

Table 6.4 Comparison of GNN-Based and Adaptive Regional Signal Controlin Yizhuang

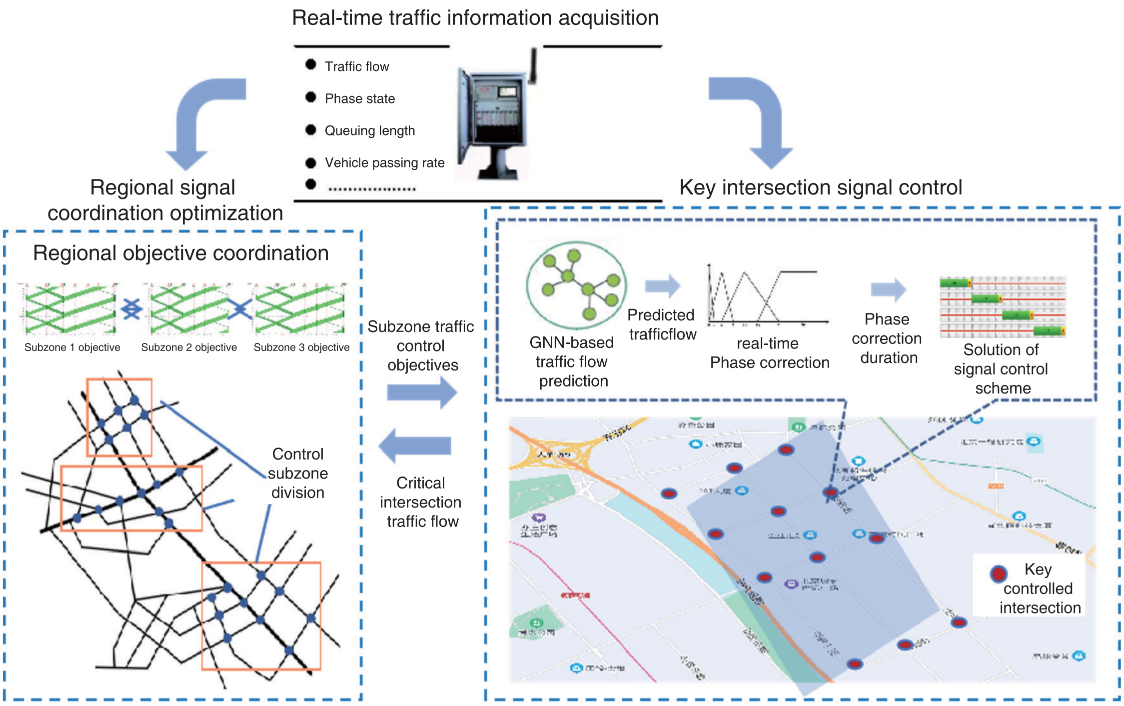


Figure 6.48 Regional Signal Control Based on GNN Traffic Prediction

07

Conclusions and Prospects

7.1
Summary of Viewpoints

Taking a comprehensive view of the entire article, the following conclusions can be drawn:

1. **VICAD can enhance safety, expand ODD, achieve fully unmanned and safe autonomous driving operations, and provide diversified support for low-level autonomous driving, thereby accelerating the commercialization of autonomous driving.** VICAD can provide comprehensive support for L4 unmanned safety operations and is also compatible with L2 autonomous driving, accelerating the coordinated development of vehicle intelligence and network connection;

2. **Intelligent infrastructure can accelerate the development of VICAD. It is necessary to categorize and gradually build intelligent roads in steps, with high-level intelligent roads possessing the ability of collaborative perception, collaborative decision-making and planning, and collaborative control.** According to different driving and travel needs, roads should be intelligently categorized and differentiated deployment plans should be formulated, with priority given to the construction and deployment of high-level intelligent roads in large and medium-sized cities and expressways, to support the commercialization of L2+ and L4 vehicles in urban and high-speed traffic environments.

3. **High-level intelligent roads offer benefits such as reducing traffic accidents, improving traffic efficiency, and promoting economic development. These benefits should be evaluated from a macroeconomic and social perspective. The investment return rate of high-level intelligent roads is usually more than five times higher.** Investment costs include upgrading road infrastructure and constructing cloud service facilities. Income can be estimated from reducing traffic accidents, improving traffic efficiency, and promoting economic development. When all vehicles are intelligently connected and high-level intelligent roads are fully covered, the investment return rate is generally more than five times higher.

7.2
Development Prospects

High-level intelligent roads and VICAD are essential for creating a safe, efficient, and convenient intelligent travel system, aligning with society's needs for a better quality of life. However, the commercialization of vehicle-infrastructure cooperation with autonomous driving is a gradual process from partial to overall, from quantitative change to qualitative change. Firstly, it requires the breakthrough of key technologies such as efficient vehicle-road communication, cloud control platform research and development, and vehicle-infrastructure cooperation system construction. Secondly, the penetration rate of intelligent vehicles and the coverage rate of intelligent roads need to reach a certain level. Finally, sufficient support should be provided in terms of policy, regulations, and standards.

Note:

1) Proportion of high-level intelligent roads: Proportion of C4 and C5 high-level intelligent roads (in large and medium-sized cities and expressways) in China

2) Share of new vehicles (L2 and above): Proportion of annual sales of autonomous vehicles (L2 and above)

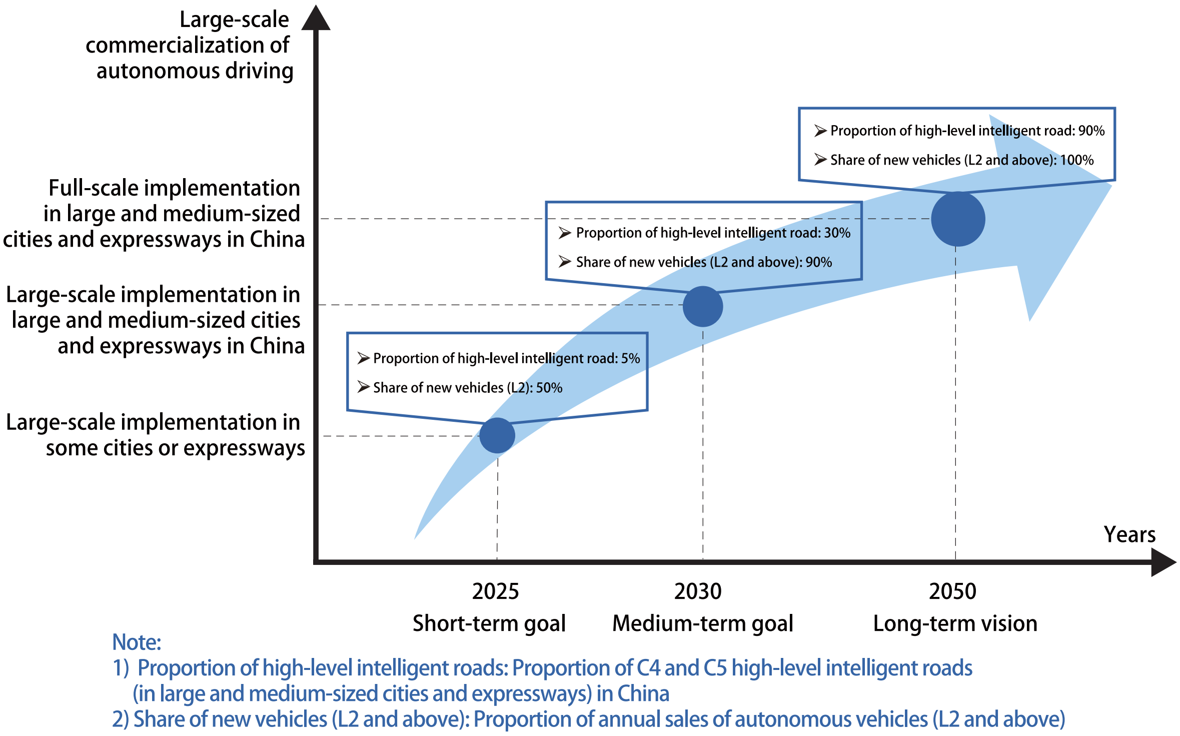


Figure 7.1 A Vision for the Commercialization of VICAD

The full-scale commercialization of VICAD can be implemented in three stages, as shown in Figure 7.1:

(1) In the short term, by 2025, the aim is to achieve commercialization on a large scale in some pilot cities and expressways, where high-level intelligent roads are available. The proportion of C4 and above high-level intelligent road mileage in urban roads and expressways will reach 5%, and the proportion of annual sales of L2 and above level new vehicles will exceed 50%. This stage achieves the continuous driving of L2 and above level autonomous driving vehicles on the high-level intelligent roads.

(2) In the medium term, by 2030, the aim is to increase the proportion of C4 and above

high-level intelligent road mileage in large and medium-sized cities and expressways in China to 30%, and the proportion of annual sales of L2 and above level new vehicles to 90%. At this stage, L2 and above level autonomous driving vehicles will be able to achieve large-scale commercialization on the intelligent roads in cities and expressways.

(3) In the long term, by the middle of this century, the goal is to achieve more than 90% coverage of C4 high-level intelligent roads in large and medium-sized cities and expressways in China. The proportion of annual sales of L2 and above level new vehicles will reach 100%, and L2 and above level autonomous driving vehicles will be able to achieve continuous autonomous driving on the intelligent roads in all large and medium-sized cities and important expressways nationwide.

7.3 Development Suggestions

As VICAD is still in its early stages of exploration and development on a global scale, there exist numerous challenges and obstacles that necessitate industry-wide collaboration to overcome.

(1) The deep integration of vehicle-infrastructure-cloud creates a highly complex system with many dimensions. Thus, the construction of a functional safety and expected functional safety system based on systems engineering is crucial. This system requires addressing a multitude of issues, such as large-scale mobile access, multi-level interoperability, low latency, and high safety and reliability, especially applicable to various complex scenarios. Therefore, from the perspective of systems engineering, it is essential to build a VICAD functional safety and expected functional safety system, clarify system architecture, system functions, application scenarios, and service content. Furthermore, specific functional requirements, performance requirements, data requirements, and safety requirements must be clearly outlined for the system's equipment and facilities to ensure the safe and reliable operation of vehicle-road collaborative automatic driving.

(2) The development of road intelligence and driving intelligence is currently not adequately coordinated. To address this issue, it is necessary to accelerate the construction and deployment of high-level intelligent roads, improve the coverage of intelligent roads, and serve VICAD, intelligent traffic management, and even smart city construction. Currently, some cities and expressways in China have planned and built a batch of automatic driving closed test fields and open test roads, but these are still in the small-scale testing and application demonstration stage. Therefore, it is essential to build high-level intelligent roads to promote the commercialization of automatic driving on a large scale.

(3) To enhance the adoption of vehicle-infrastructure communication technology and

increase the number of connected terminals, continued development of communication technology supporting VICAD and a range of vehicle-infrastructure collaborative applications is crucial. Deploying more RSUs in cities and highways, speeding up the production of C-V2X, and deploying these technologies on a smaller scale, such as in a single city or region, are recommended to improve the penetration rate and reduce costs. Additionally, combining C-V2X products with user-friendly apps, mini-programs, and navigation maps can enhance the usability of these technologies. High-level VICAD requires higher-performance technology support, such as NR V2X or 5G, with a latency requirement of less than 10ms and a transmission reliability of no less than 99.9%.

(4) The successful deployment of VICAD depends on innovative application services and business models across industries and regions. Interconnectivity is a significant challenge in VICAD, as various factors such as vehicle data application, road sensing facilities, road signal control data, and road toll systems affect its effective promotion. Overcoming these challenges requires a deeper investigation and gradual promotion, building on the success of DSRC, and learning from its limitations. The advantages of evolving C-V2X should be fully utilized, and new application services and business models that serve VICAD should be explored.

(5) The development of VICAD is supported industry policies and standards. As VICAD progresses, regulatory research and standard revisions must be conducted at various stages. Policies and regulations have been put in place to facilitate public road testing of autonomous driving and speed up its nationwide adoption. Technical standards have been established to support autonomous driving, intelligent network connectivity, and vehicle-infrastructure cooperation. However, crucial technical standards such as road infrastructure, cloud-based control platforms, functional safety, and expected functional safety need immediate development. Collaboration between standardization organizations across various industries, including automobiles, communications, electronic information, transportation, and safety, must be strengthened to create a comprehensive regulatory system for VICAD.

08

Appendix

Appendix A: Map Reference Position Protocol

The seamless and secure flow of dynamic layer data across different map providers, car manufacturers, and module platforms is a key element that must be considered when updating maps. To address a series of issues arising from inconsistencies in coordinate systems and version mismatch of map updates in dynamic high-precision maps, a map reference position protocol can be used as a solution. The map reference position protocol defines a set of semantically meaningful ground reference feature locations that are relatively stationary, such as the intersection of traffic flow arrows, stop lines, and lane lines, as the map reference points. During the coordinate transmission process, the reference point ID and offset value are used for transmission. The endpoint uses the linear reference value and its own stored static map data to calculate the dynamic map update information, avoiding the transmission of original coordinates and ensuring data security. Figure A.1 shows a schematic diagram.

The advantages of the map reference position protocol are as follows:

1) Seamless flow of dynamic map information among multiple heterogeneous maps: The map reference position protocol breaks down the barriers to dynamic map information flow and enables the transfer of dynamic information among different precision levels and different map providers, ensuring the accuracy of geographic information and consistency in expression and understanding.

2) Enhanced geographic information security by avoiding the exposure of original coordinates during transmission: The use of linear reference avoids the direct transmission of geographic coordinates, reducing the possibility of information interception and reverse calculation.

3) Increased density of transmission information and simplified complexity of dynamic information use: By using linear reference, complex vector line data can be expressed with several relative positions, greatly reducing the amount of transmitted data. The map matching process is also simplified, and the complexity of relative spatial relationship calculation is reduced.

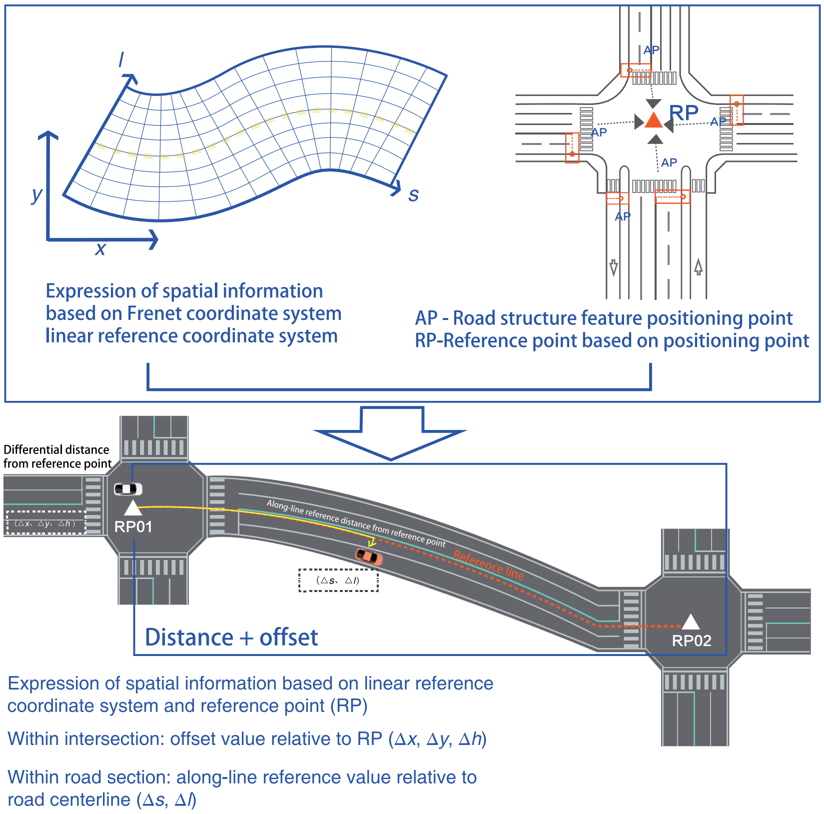


Figure A.1 Coordinate System Based on Reference Position

Appendix B: Safety Evaluation Experiment for VICAD

This experiment aims to quantitatively analyze different autonomous driving systems. To achieve this, a traffic simulation platform is developed through a secondary development based on the autonomous driving simulator Carla. This platform enables the simulation of driving behavior using various perception, decision-making and control algorithms, allowing the comparison and analysis of system results based on different evaluation metrics.

Through analysis and summary of Baidu's test data collected from the real world and public data sets in the field of autonomous driving, four typical scenarios are selected in the experiment, including the pedestrian ‘blind zone’, unprotected left turn, anomalous obstacles, and abnormal traffic conditions. These scenarios represent the safety issues and edge scenarios that are highly concerned in the field of autonomous driving. Real data is used to model the initial parameter distribution of each scenario, in order to render and construct high-fidelity experimental scenarios in the simulation platform.

For each typical scenario, three kinds of controlled experiments are conducted in terms of single-vehicle intelligence, vehicle-infrastructure cooperative perception, vehicle-infrastructure cooperative decision-making and control, each conducted 1,000 times. The experimental results are statistically analyzed from the evaluation dimensions of safety and passing efficiency, providing theoretical references for the quantitative analysis and evaluation of autonomous driving solutions.

B.1 Scenario distribution model

Through the statistical analysis of nearly 30,000 real-world traffic flow trajectories provided by Baidu Apollo, the scenario distribution function under free traffic flow is fitted by using methods such as maximum likelihood estimation [1], [2].

Among them, the time headway distribution of vehicle distance in non-intersection environment follows a negative exponential distribution:

$$P(h) = 0.1742\, e^{-0.1742h};$$

The speed distribution of vehicles in non-intersection environments follows a lognormal distribution:

$$P(v) = \frac{1}{0.4857v\sqrt{2\pi}} e^{-\frac{(lnv-1.8304)^2}{0.4718}}, v > 0;$$

The speed distribution of vehicles in intersection environments conforms to a lognormal distribution:

$$P(v) = \frac{1}{0.3827v\sqrt{2\pi}} e^{-\frac{(\ln v-1.5853)^2}{1.5269}}, v > 0。$$

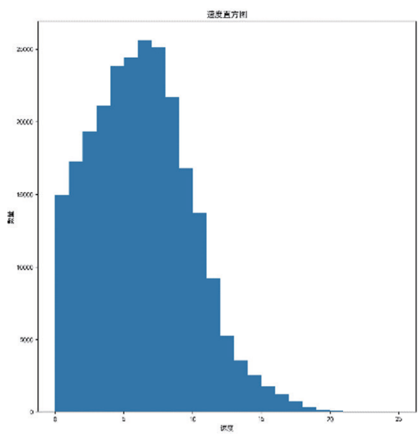


Figure B.1 Histogram of Vehicle Speed in Intersection Environments

In the pedestrian 'blind zone' scenario, the hyperparameters $\{\theta_0\}=\{v_1,v_2,d_1,h_2\}$ are defined, where v_1 is the speed of the ego vehicle, v_2 is the speed of the following vehicle, h_2 is the time headway[3], d_1 is the distance between the ego vehicle and the roadside equipment, and d_2 is the distance between the following vehicle and the roadside equipment, which can be obtained by $d_2=d_1+abs(v_2-v_1)h_2$. Both vehicle speeds v_1 and v_2 follow a log-normal distribution. The pedestrian speed is assumed to be constant, and the distribution of h_2 follows a negative exponential distribution[4]. According to the state distribution of real vehicle data, the distribution of d1 is approximately uniform.

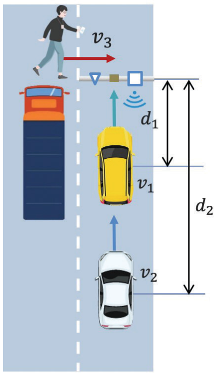


Figure B.2 Pedestrian 'Blind Zone

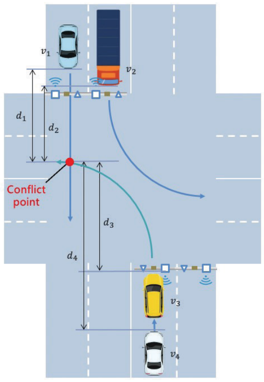


Figure B.3 Unprotected Left Turn

In the unprotected left turn scenario, the hyperparameter $\{\theta_0\}=\{v_1,v_2,v_3,v_4,d_1,d_2,d_3,h_4\}$ are defined, where v_1 is the speed of the oncoming vehicle 1, v_2 is the speed of the obstructing vehicle 2, v_3 is the speed of left-turning ego vehicle 3, v_4 is the speed of following vehicle 4, and the collision point between the left-turning vehicle 3 and the oncoming vehicle 1 is defined as the conflict point [5]. d_1 represents the distance between the straight-driving vehicle 1 and the conflict point. d_2 is the distance between the obstructing vehicle 2 and the parallel line where the conflict point is located. d_3 is the distance between the left-turning vehicle 3 and the parallel line where the conflict point is located, and h_4 is the time headway between vehicles 3 and 4. According to the state distribution of real vehicle data, the distributions of v_1, v_2 and v_3 all follow a log-normal distribution, and the distributions of d_1, d_2 and d_3 are assumed to be uniform. The distribution of h_4 follows a negative exponential distribution.

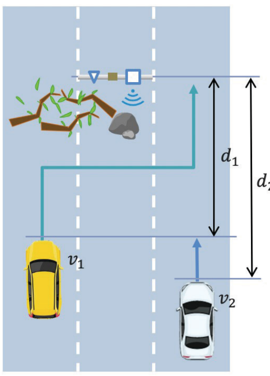


Figure B.4 Anomalous Obstacles

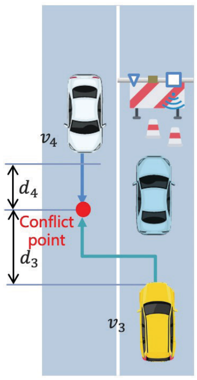


Figure B.5 Abnormal Traffic Conditions

In the anomalous obstacle scenario, the hyperparameters $\{\theta_0\}$ = $\{v_1, v_2, d_1, d_2\}$ are used, where v_1 is the speed of the leading vehicle 1 in the left lane, v_2 is the speed of the following vehicle 2 in the right lane, and d_1 and d_2 are the distances between vehicles 1 and 2 and the roadside equipment [6] respectively. The speeds of both vehicles v_1 and v_2 follow a uniform distribution in accordance with the speed regulations for urban roads [7], [8]. According to the state distribution of real vehicle data, the distribution of d_1 and d_2 is approximately uniform.

In abnormal traffic conditions, the hyperparameters $\{\theta_0\}$ = $\{v_1, v_2, v_3, v_4, d_3, d_4\}$ are used, where v_1 and v_2 are the speeds of other non-autonomous vehicles 1 and 2 driving through the area before the abnormal situation occurs. Vehicle 5 is a stationary vehicle parked in front of the road construction zone. v_3 is the speed of vehicle 3 which needs to decide whether to retrograde instead of waiting after vehicle 5, and v_4 is the speed of the oncoming vehicle 4 in the opposite direction. The collision point between vehicle 3 and oncoming vehicle 4 is defined as the conflict point, and d_3 is the distance between vehicle 3 and the conflict point, while d_4 is the distance between vehicle 4 and the conflict point. According to the state distribution of real vehicle data, the speeds v_1, v_2, v_3, and v_4 are approximately log-normally distributed, while $1/d_3$ and $1/d_4$ approximately follow a Poisson distribution [2], [9] and [15].

B.2 Perceptual model

In this experiment, the perception model takes images collected by RGB and depth cameras as inputs. The perception model, based on the semantic segmentation model, understands the environment of the vehicle and provides perceptual results to downstream decision-making models for their reference. Generally, perception results are output as pixel-level semantic annotations and anomaly annotations.

The semantic segmentation model cannot make accurate predictions when encountering anomalies—inputs that are not from the distribution of the training set. As a result, it is difficult to deploy the semantic segmentation model under scenarios with stringent safety requirements. An anomaly detection algorithm is needed to detect anomaly objects such as unexpected obstacles on the road. We need to verify the performance of the anomaly detection algorithm on anomaly detection datasets during training.

Commonly used anomaly detection datasets include Fishyscapes [16], RoadAnomaly [17], StreetHarzards [18], Road Obstacles [19], and Lost and Found [20]; Some anomalies in the images are taken from the image dataset of objects, while the others are real anomalies in the scene.

Among existing anomaly detection algorithms, methods represented by Synboost [21] combine the results of multiple models such as semantic segmentation and image generation models. They provide good results but their speeds are slow. Methods represented by SML [22] adjust the outputs of existing semantic segmentation models by normalizations to obtain the thresholds of anomaly segmentation. These methods have better real-time performance. In this experiment, we use SML for anomaly segmentation.

SML [22] proposes to standardize the output scores of semantic segmentation models. When a classification algorithm classifies a pixel into an object class, its prediction score is usually higher if the pixel actually belongs to that object class than when the object does not belong to that object class. However, this is not always the case. Therefore, SML proposes to standardize output scores to make scores more different for the above two situations. It reduces overlaps of output scores from the two different situations, making it easier to distinguish one situation from the other. To standardize output scores, the algorithm computes the means μc and variances σ2c of output scores for each object class in the training set.

$$\mu_c = \frac{\sum_i \sum_{h,w} \mathbb{1}\left(\widehat{\boldsymbol{Y}}_{h,w}^{(i)} = c\right) \cdot \boldsymbol{L}_{h,w}^{(i)}}{\sum_i \sum_{h,w} \mathbb{1}\left(\widehat{\boldsymbol{Y}}_{h,w}^{(i)} = c\right)}$$

$$\sigma_c^2 = \frac{\sum_i \sum_{h,w} \mathbb{1}\left(\widehat{\boldsymbol{Y}}_{h,w}^{(i)} = c\right) \cdot \left(\boldsymbol{L}_{h,w}^{(i)} - \mu_c\right)^2}{\sum_i \sum_{h,w} \mathbb{1}\left(\widehat{\boldsymbol{Y}}_{h,w}^{(i)} = c\right)}$$

In the above formula, i represents the i-th training sample.

After obtaining means and variances, the model standardizes output scores when running on the test set. The standardized maximum score $S_{h,w}$ for each position h,w is defined as:

$$\boldsymbol{S}_{h,w} = \frac{\boldsymbol{L}_{h,w} - \mu_{\widehat{\boldsymbol{Y}}_{h,w}}}{\sigma_{\widehat{\boldsymbol{Y}}_{h,w}}}$$

After standardizing scores, some false positives and false negatives still exist at the prediction boundaries of the model. To address incorrect predictions at prediction boundaries, the algorithm performs iterative suppression for prediction results at boundary regions. It gradually broadcasts standardized maximum scores of non-boundary regions to surrounding boundary regions. Specifically, it sets the width of boundaries to a specific value and gradually decreases this value. Given the boundary width r_i during the i-th iteration and the semantic segmentation output $\widehat{Y}_i$, the mask $M^{(i)} \in R^{H\times W}$ for each non-boundary pixel at h,w is:

$$\boldsymbol{M}_{h,w}^{(i)} = \begin{cases} 0, & \text{if } \exists h', w' \text{ s.t., } \widehat{\boldsymbol{Y}}_{h,w} \neq \widehat{\boldsymbol{Y}}_{h',w'} \\ 1, & \text{otherwise} \end{cases}$$

The above formula is used to compute each pair of h' and w' that satisfies

$$|h - h'| + |w - w'| \leq r_i$$

Next, the algorithm employs boundary-aware average pooling (BAP). For a boundary pixel b and its receptive field R, the boundary-aware average pooling is:

$$BAP\left(\boldsymbol{S}_{\mathcal{R}}^{(i)}, \boldsymbol{M}_{\mathcal{R}}^{(i)}\right) = \frac{\sum_{h,w} \boldsymbol{S}_{h,w}^{(i)} \times \boldsymbol{M}_{h,w}^{(i)}}{\sum_{h,w} \boldsymbol{M}_{h,w}^{(i)}}$$

In the above formula, $S_R^{(i)}$ and $M_R^{(i)}$ represents the receptive field on $S^{(i)}$ and $M^{(i)}$, respectively; $(h,w) \in R$ enumerates pixels in R.

Since boundary suppression can only update boundary pixels, it cannot address anomaly values in non-boundary regions. This algorithm employs dilated smoothing to address anomaly values in non-boundary regions. Boundary suppression uses Gaussian kernels because they can remove noises. With known standard deviation σ and convolutional filter of size k, the kernel weight $K \in R^{k \times k}$ at position i,j is defined as:

$$\boldsymbol{K}_{i,j} = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{\Delta i^2 + \Delta j^2}{2\sigma^2}\right)$$

In the above formula, $\Delta i = i - \frac{k-1}{2}$ and $\Delta j = j - \frac{k-1}{2}$ are the displacement of i,j from the center.

In the vehicle-infrastructure cooperation scenario, an SML model is deployed at the vehicle-end and the road end simultaneously. First, the pixel-level anomaly detection results of the road-end are mapped into the world coordinate system according to the pose and depth information of the road-end camera, and then based on the vehicle-end camera's pose, the abnormal points in the world coordinate system are projected to the perspective of the vehicle; for the two sets of semantic segmentation results projected from the vehicle end and the road end to the vehicle, if the road end and the vehicle end agree that a certain point is abnormal, or the semantic segmentation results of a certain point on the road end and the car end are inconsistent, the corresponding point will be treated as the abnormal in both cases. The experimental results show that the performance of the perception model under the vehicle-infrastructure cooperation using the above method is better than that under the single-vehicle condition.

In the vehicle-infrastructure cooperation scenario, the SML model is deployed at the vehicle-end and the road-end simultaneously. First, the pixel-level anomaly detection results of the road-end are projected into the world coordinate system according to the pose and depth information of the road-end camera, and then based on the vehicle-end camera's pose, the abnormal points in the world coordinate system are projected to the perspective of the vehicle. Considering the semantic segmentation results of the vehicle-end and those projected from the road-end to the vehicle-end, if the road-end and the vehicle-end agree that a certain point is anomalous, or the semantic segmentation results of a certain point on the road end and the vehicle end are inconsistent, the corresponding points will be treated as the abnormal in both cases. The experimental results show that the performance of the perception model under the vehicle-infrastructure cooperation using the above method is better than that under the single-vehicle condition.

B.3 Decision-making and control model

The decision-making and control model in this experiment is obtained based on the improved version of CARLA's decision-making and control method [4]. Corresponding strategies are defined for differenct driving states. The transitions between states are executed based on the estimates provided by the perception module and the topological information provided by the global planner. The current pose, velocity, and planned navigation points of the autonomous vehicle are sent to the PID controller to control the steering, throttle, and brake. The PID controller demonstrates good robustness to the possible slow response in the simulator. The decision control models for five different driving states are defined as follows:

(1) In the state of driving along the road, based on the mask of the current lane calculated by a segmentation algorithm, the local planner selects a series of points that maintain a fixed distance from the right edge of the road as subsequent navigation points.

(2) In the state of turning left at the intersection, due to the absence of lane lines, the far distance to the target lane, and the limited field of view of the front camera, a relatively complex decision-making and planning strategy is required. The navigation point towards the center of the intersection is calculated with a predefined inclination angle to improve the recognition of the target lane. Then, a smooth trajectory is planned from the center of the intersection to the target lane.

(3) In the state of turning right, a strategy similar to turning left state is adopted. However, since the target lane for turning right is closer, fewer navigation points need to be planned and only forward information is required without additional supplementary information.
(4) In the state of driving straight at the intersection, the decision-making and control strategy is similar to that in the state of driving along the road.

(5) In the state of an emergency stop, when the accumulated probability of detecting dynamic obstacles exceeds a predefined threshold, indicating potential danger, the system will activate the emergency stop mode and request the controller to interrupt the continuous control immediately.

B.4 Evaluation model

The evaluation model consists of three components: the vehicle safety evaluation model, the pedestrian safety evaluation model, and the traffic efficiency evaluation model.

The vehicle safety evaluation model uses real data to simulate driving conditions based on the scenario's initial parameters. This is achieved when the vehicle model supports single-vehicle intelligence, vehicle-infrastructure cooperative perception, and vehicle-infrastructure cooperative decision-making and control. The model's output is the driving collision rate in the large-scale simulation results of specific scenarios, and the absolute probability is calculated using statistical-based vehicle collision probability [23], [24]. The statistical-based vehicle collision probability is $P_v = \frac{n_C}{N} * p_e$, where n_c is the number of vehicle collision tests, N is the total tests, and p_e is the occurrence probability of the scenario. The collision rate in the pedestrian 'blind zone' scenario is estimated from the CIDAS database, which describes the collision probability of autonomous vehicles with pedestrians and other vehicles. The occurrence probability of other scenarios is estimated based on small-scale real data samples.

The pedestrian safety evaluation model is based on a real database and uses risk factor analysis to obtain the relationship model between collision speed and serious pedestrian injury or death probability[25], [26]. This model is applied to the evaluation of pedestrian safety in Scenario I.

A general pedestrian safety evaluation model, the logistic regression-risk curve model [27], [28], is also used. In Jacques Saadé's study [25], this model is fitted using the real dataset of the VOIESUR Accident Database, which includes 8,500 incidents of pedestrian death or injury caused by traffic accidents [25], [29]. Cases of pedestrian injury or death caused by the loss of vehicle control are excluded. Only cases of pedestrian injury or death caused by the first vehicle collision, rather than the second, are considered. Furthermore, it should be noted that situations in which the vehicle does not collide with pedestrians are regarded as screening conditions. Finally, among the 5,163 cases that meet these criteria, 2,483 cases have sufficient information. At the same time, correction factors are used for the remaining cases to compensate for information shortages, allowing the data to be utilized to the greatest extent possible.

Regarding risk factor analysis methods, the logistic regression-risk curve model is employed to assess the impact of various factors on the death rate. Specifically, this model evaluates the influence of different impact velocities, pedestrian ages, impacted body parts, vehicle production years, hood heights, and pedestrian walking directions on the death rate by calculating the dominance ratio. Among these factors, impact velocity (V) and pedestrian age (A) are identified as the most robust and significant influencing factors [25]. Furthermore, Jacques Saadé's [25] research includes a 2*2 experiment in which he tests the accuracy of four combinations from two independent variable relationships (V+A, V^2+A) and two regression models (comprehensive-loglog, Logit) in predicting pedestrian death rate or serious injury rate.

The Akaike information criterion (AIC) and error term are used.

$$cloglog(p) = \ln(-\ln(1-p)) \qquad logit(p) = ln(\frac{p}{1-p})$$

PERFORMANCE CRITERIA OF DIFFERENT RISK CURVE MODELS FOR BOTH K AND KSI OUTCOMES

Model	AIC K	ΔN K	AIC KSI	ΔN KSI
Cloglog (V+A)	56.3559	1.1764	293.0908	2.125
Logit (V+A)	56.8511	0	296.0625	0
Cloglog (V^2+A)	55.8829	0.0773	291.2463	3.893
Logit (V^2+A)	56.1882	0	291.7609	0

Table B.1 Regression Error Analysis Results [25]

The experimental findings reveal that the Logit(V^2+A) combination has the least loss. Consequently, a relationship model and risk curve are established to examine the impact of impact velocity (V) and pedestrian age (A) on pedestrian death or serious injury rates.

$$P_{KSI} = \frac{\exp(-2.9893 + 0.0013 * V^2 + 0.0286 * A)}{1 + \exp(-2.9893 + 0.0013 * V^2 + 0.0286 * A)}$$

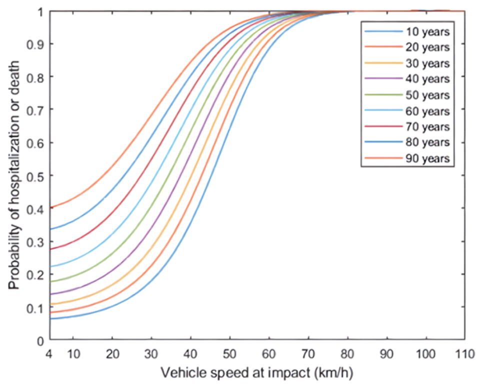


Figure B.6 Risk Curve for Pedestrian Safety [25]

Drawing on the research conducted by Jacques Saadé [25], the collision occurrence probability (P_h) is incorporated under the conditions of the simulation experiment, and it can be derived from the conditional probability formula. The function formula for the pedestrian safety evaluation model in the simulation experiment for Scenario I is as follows:

$$\mathcal{L}(P, V, A) = P_h * \frac{\exp(-2.9893 + 0.0013 * V^2 + 0.0286 * A)}{1 + \exp(-2.9893 + 0.0013 * V^2 + 0.0286 * A)}$$

Among the factors, pedestrian age (A) is based on real data statistics of the high-frequency travel accident population, which is found to be 40 years old [30]. As evident from the aforementioned function formula of the pedestrian safety evaluation model, a lower collision probability (P_h) and impact velocity (V) correspond to a lower likelihood of pedestrian injury or death. This finding demonstrates that the simulation model utilized for testing has a high level of safety.

The traffic efficiency evaluation model assesses the time (T) required for a target vehicle to pass through a designated traffic area in four distinct scenarios while guided by single-vehicle intelligence, vehicle-infrastructure cooperative perception, and vehicle-infrastructure cooperative decision-making and control. For each scenario, the entry and exit times of the target vehicle in the demarcated area were recorded to estimate the passing time. The area was defined differently for each scenario. For instance, Scenario I involved a rectangular area that encompassed stationary vehicles in the left lane and the entire intersection, while Scenario II covered the intersection and the region two vehicle bodies away from the pedestrian crossing in each direction. The primary objective of this evaluation model was to measure the impact of different decision-making and control solutions on traffic efficiency. In a single experiment that considered the processing time of traffic accidents resulting from collisions, the average transit time was calculated to be 33 minutes in the case of vehicle collisions [31] and 35 minutes in the event of pedestrian collisions, using data from public transportation datasets [32].

The performance of single-vehicle intelligence, vehicle-infrastructure cooperative perception, and vehicle-infrastructure cooperative decision-making and control was comprehensively assessed in specific scenarios using the comprehensive safety and efficiency evaluation model, as presented in references [33], [34] and [35].

Abbreviations

3GPP: 3rd Generation Partnership Project
4G: The 4th generation mobile communication technology
5G: The 5th generation mobile communication technology
AD: Autonomous Driving
ADAS: Advanced Driving Assistance System
AI: Artificial Intelligence
ASV: Advanced Safety Vehicle
AV: Autonomous Vehicle
BSM: Basic Safety Message
C-V2X: Cellular-V2X
C-ITS: China ITS Industry Alliance
CAN: Controller Area Network
CAV: Cooperated Automated Vehicle
CCSA: China Communications Standards Association
CSAE: Society of Automotive Engineers of China
CVPR: IEEE Conference on Computer Vision and Pattern Recognition
DCU: Domain Controller Unit
DOT: U.S. Department of Transportation
DSRC: Dedicated Short Range Communication
DSSS: Driving Safety Support Systems
ECU: Electronic Control Unit
ERTAC: European Road Transport Research Advisory Council
ETC: Electronic Toll Collection
ETSI: European Telecommunications Standards Institute
EUHT: Enhanced Ultra High Throughput (ultra-high-speed wireless communication system)
GPS: Global Positioning System
GNN: Graph Neural Network
GNSS: Global Navigation Satellite System
HUD: Head Up Display
HV: Host Vehicle
HWP: High Way Pilot
ICT: Information and Communications Technology

ICV: Intelligent Connected Vehicle

IDM: Intelligent Driver Model

IEEE: Institute of Electrical and Electronics Engineers

IMT: International Mobile Telecommunications

IMU: Inertial Measurement Unit

IoT: Internet of Things

IRR: Internal Rate of Return

ISAD: Infrastructure Support Levels for Automated Driving

ISO: International Standard Organization

ITS: Intelligent Transportation Systems

LTE: Long Term Evolution

LTE-V2X: LTE Vehicle to Everything (LTE-based vehicle wireless communication technology)

MaaS: Mobility as a Service

MCU: Microcontroller Unit

MEC: Multi-access Edge Computing

NR-V2X: new radio V2X

NV: Normal Vehicle (ordinary vehicle without a communication system)

OBU: On-Board Unit

ODD: Operational Design Domain

OEM: Original Equipment Manufacturer

OS: Operating System

OTA: Over-the-Air Technology

PC5: Direct communication interface

PNC: Planning and Control (autonomous driving planning and control, including navigation, prediction, decision-making, planning, control, etc.)

RSCU: Road Side Computing Unit

RSI: Road Side Information

RSM: Road Safety Message

RSU: Road Side Unit

RTK: Real-time Kinematic (real-time dynamic carrier phase difference)

RTMP: Real-time Messaging Protocol

RTP: Real-time Transport Protocol

RTSP: Real-time Streaming Protocol

SAE: Society of Automotive Engineers

SOTIF: Safety of The Intended Functionality

SPAT: Signal Phase and Timing Message

SSM: Sensor Sharing Message

T-BOX: Telematics BOX (on-board remote information processor)

TOPS: Tera Operations Per Second (unit of processor computing power)

TTC: Time to Collision

UMADE: Unified Model of Autonomous Driving Evaluation

Uu: Cellular network communication interface

UWB: Ultra Wide Band

V2I: Vehicle to Infrastructure (communication between vehicle equipment and roadside infrastructure)

V2N: Vehicle to Network

V2P: Vehicle to Pedestrians (communication between on-board unit and pedestrian devices)

V2V: Vehicle to Vehicle (vehicle-vehicle communication)

V2X: Vehicle to Everything

VICAD: Vehicle Infrastructure Cooperated Autonomous Driving

VICAD-SRM: Vehicle Infrastructure Cooperated Autonomous Driving Safety Reward Model

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