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Research on Technology Forms and Industrial Trends of the Internet of Vehicles

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Abstract

As the core support of the intelligent connected vehicle industry, the Internet of Vehicles (IoV) is a key carrier for the integrated development of "electrification, intelligence, and connectivity". This paper systematically sorts out the evolution process of IoV technology forms, and analyzes its core technical architecture and practical characteristics from the Perception Layer, Network Layer, and Application Layer. Combining global and China's industrial development data, it explores the core trends such as industrial ecological reconstruction and technological integration innovation. It also deeply discusses the current challenges including technical bottlenecks, cost pressures, and standard coordination, and puts forward optimization suggestions from the dimensions of technological R&D, industrial collaboration, and policy support. The research shows that IoV is transforming from "single communication service" to "global intelligent collaboration", and building a safe, reliable, and independent technological and industrial system has become the core development goal.

Keywords

Internet of Vehicles, V2X Technology, 5G-Advanced, Industrial Ecology, Intelligent Collaboration.

1. Introduction

As the global automotive industry enters the deep-water phase of the "Four Newizations" transformation, the Internet of Vehicles (IoV) has evolved from an auxiliary communication tool to a core infrastructure that reconstructs the value of automobiles. Through the collaboration of on-board terminals, roadside equipment, communication networks, and cloud platforms, IoV realizes the data interaction and intelligent decision-making of all elements in the "vehicle-person-road-cloud" ecosystem, and serves as a key support for improving the safety of autonomous driving and optimizing traffic efficiency. According to the data from the "2024 White Paper on the Development of China's IoV Industry" released by CATARC, the global IoV market scale exceeded 1.2 trillion yuan in 2024, among which China's market scale reached 520 billion yuan, accounting for more than 40%. The penetration rate of new vehicles equipped with IoV functions reached 68% globally, while China's market penetration rate was as high as 82%, making it the core engine of global IoV development[1].

Technically, breakthroughs in technologies such as 5G-Advanced (5G-A), Vehicle-to-Everything (V2X), and AI large models have provided computing power and communication guarantees for IoV. Policy-wise, intensive policies such as China's "Dual Intelligence" pilot (coordinated development of smart cities and intelligent connected vehicles) and the EU's "Intelligent

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Connected Vehicle Regulations" have been introduced, promoting IoV from technological R&D to large-scale application. However, at the same time, issues such as technical integration barriers, data security risks, and insufficient industrial collaboration in IoV have become increasingly prominent, making it urgent to systematically sort out the technology forms and industrial trends to provide theoretical support for the high-quality development of the industry.

The research significance of this paper is reflected in two dimensions: Theoretically, it constructs an analytical framework of "technology form - industrial characteristic - development path", filling the gap in the integrated analysis of technology and industry in existing IoV review studies. Practically, it clarifies the core technology breakthrough directions and industrial collaboration priorities of IoV, providing decision-making references for chip enterprises, vehicle manufacturers, communication operators and other entities.

2. Evolution and Core Architecture of IoV Technology Forms

The technology form of IoV has gone through three stages of evolution: "single communication - local interconnection - global collaboration". The first stage (2010-2019) focused on in-vehicle information services, realizing basic functions such as navigation and entertainment, with representative technologies including 3G/4G and in-vehicle T-BOX. The second stage (2020-2023) entered the stage of local interconnection between vehicles and vehicles, and vehicles and roads. 5G and primary V2X technologies were implemented, supporting L2-L3 level autonomous driving. The third stage (starting from 2024) moves towards "vehicle-person-road-cloud" global collaboration, integrating 5G-A, high-level V2X, and AI to support L4+ level autonomous driving and the construction of intelligent transportation systems. Currently, IoV has formed a three-level technical architecture of "Perception - Network - Application", with each level collaborating to support global intelligence[2].

2.1. Perception Layer: "Nerve Endings" for Global Data Collection

The Perception Layer is the core of IoV data collection. It realizes full coverage of "vehicle-side - road-side" data through on-board sensors and road-side perception equipment, solving the problem of "environmental perception blind spots". The core technologies and equipment include:On-board perception equipment: With lidar, high-definition cameras, and millimeter-wave radar as the core, supplemented by ultrasonic radar to achieve 360° environmental perception. For example, Tesla's HW4.0 platform is equipped with 12 ultrasonic radars and 4 lidars, with an environmental recognition accuracy of 0.1 meters. Xpeng G9 adopts a perception system driven by dual Orin-X chips, which can identify 120 target objects simultaneously.Road-side perception equipment: Millimeter-wave radars, high-definition cameras, and edge computing nodes deployed at intersections and accident-prone road sections to realize "vehicle-side perception + road-side blind spot compensation". For instance, the road-side equipment deployed in the Suzhou vehicle-road collaboration pilot can share real-time information of traffic participants within 500 meters with vehicles, reducing the decision-making response time of autonomous driving by 30%.Data fusion technology: Eliminating perception errors of a single device through multi-sensor data fusion (multi-source heterogeneous data fusion algorithm). For example, Huawei's MDC 810 domain controller adopts a "lidar + camera" data fusion solution, with an obstacle recognition accuracy of 99.2%[3].

2.2. Network Layer: "Communication Hub" for Efficient Data Transmission

The Network Layer is the core carrier for IoV data transmission, which needs to meet the automotive-grade requirements of "low latency, high reliability, and large bandwidth". Currently, it builds a communication system centered on 5G-A and V2X technologies:5G-A

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technology: As the core communication technology of IoV, 5G-A achieves performance breakthroughs of "latency ≤ 1ms, bandwidth ≥ 10Gbps, and connection density of $10^6/km^2$", supporting real-time updates of high-definition maps and instantaneous transmission of vehicle-road collaboration commands. For example, Qualcomm's Snapdragon Automotive 5G Modem X75 can realize parallel transmission of V2X communication and in-vehicle entertainment data without mutual interference.V2X technology: Divided into two major technical routes: Cellular V2X (C-V2X) based on cellular networks and Dedicated Short-Range Communications (DSRC) based on dedicated short-range communications. Among them, C-V2X has become the mainstream due to its strong compatibility. C-V2X covers four major application scenarios: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Cloud (V2C). For example, V2V communication can realize real-time sharing of vehicle emergency braking information, reducing the rear-end collision rate by 60%; V2I communication can obtain traffic signal timing, optimizing vehicle traffic efficiency by 15%.Edge computing nodes: Edge computing equipment deployed on the base station side realizes "local data processing + nearby transmission", reducing the round-trip latency to the cloud. For example, the IoV edge nodes deployed by China Mobile in the Beijing-Tianjin-Hebei region reduce the processing latency of autonomous driving decision-making data from 50ms to less than 5ms.

2.3. Application Layer: "Core Carrier" for Value Realization

The Application Layer is the ultimate embodiment of the value of IoV technology, focusing on three major scenarios: autonomous driving, intelligent transportation, and in-vehicle services, forming a diversified application ecosystem:Autonomous driving: IoV supports the upgrade of autonomous driving from "single-vehicle intelligence" to "vehicle-road collaborative intelligence". For example, Baidu's Apollo RT-6 autonomous vehicle obtains road-side traffic information through V2X, increasing the traffic efficiency at complex intersections by 40% and reducing accident risks by 70%.Intelligent transportation: An intelligent traffic management system built based on IoV data to realize dynamic regulation of traffic flow. For instance, the Guangzhou IoV pilot adjusts the duration of traffic signals dynamically by analyzing real-time operation data of 100,000 vehicles, reducing the regional congestion index by 25%.In-vehicle services: Covering scenarios such as in-vehicle entertainment, remote operation and maintenance, and in-vehicle payment. For example, Huawei's intelligent cockpit realizes seamless connection of "mobile phone - vehicle machine - smart home" through IoV, allowing users to control smart home devices in the car; Tesla realizes remote firmware updates through IoV, and in 2024, more than 8 million vehicles worldwide obtained automatic parking functions through OTA upgrades[4].

3. Current Status and Core Trends of IoV Industry Development

3.1. Industry Development Status: Coexistence of Scale Expansion and Ecological Reconstruction

The global IoV industry has entered a stage of large-scale development, with various links of the industrial chain accelerating integration. China has become a core growth pole relying on policy support and market advantages. In terms of market scale, the global core IoV industry scale reached 1.2 trillion yuan in 2024, a year-on-year increase of 28%, of which China's market scale was 520 billion yuan, accounting for 43.3%. In terms of industrial chain structure, the chip, communication, vehicle manufacturing, and service links show the characteristics of "accelerated localization of chips, communication operators leading network construction, and vehicle manufacturers integrating ecosystems":

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Chip link: Qualcomm and Intel dominate the high-end IoV chip market (with a combined share of over 60%), but domestic chip enterprises are accelerating their breakthroughs. Huawei's Balong 5000 C-V2X chip and Ziguang Guowei's automotive-grade MCU have been mass-produced, and the market share of domestic IoV chips increased to 18% in 2024.

Communication link: China Mobile and China Telecom lead the construction of domestic IoV networks. By the end of 2024, more than 150,000 dedicated IoV base stations have been built in China, covering major cities and expressways nationwide. Internationally, the C-V2X networks deployed by Verizon and AT&T in North America have served more than 5 million vehicles[5].

Vehicle manufacturing link: New energy vehicle companies have become the main force in IoV applications. The penetration rate of IoV in new vehicles of BYD, Tesla, NIO and other companies has reached 100%. Traditional vehicle manufacturers are accelerating their transformation, and the penetration rate of IoV in new vehicles of Volkswagen and Toyota increased to 75% and 68% respectively in 2024.

Service link: The in-vehicle service market presents a diversified development trend. Leading enterprises have emerged in segmented fields such as navigation (Amap, Baidu Maps), entertainment (Tencent Auto Link), and operation and maintenance (Bosch IoV). In 2024, the scale of China's in-vehicle service market reached 89 billion yuan, a year-on-year increase of 35%.

3.2. Core Industry Trends: Technology Integration and Ecological Collaboration

The traditional IoV industrial chain is a linear structure of "chip - communication - vehicle manufacturing - service", and it has now evolved into a "multi-subject collaborative" networked ecosystem. The core characteristics are "cross-border integration" and "emergence of ecological leaders". For example, Huawei has built a full-stack solution of "chip (Balong series) - communication (5G-A) - domain controller (MDC) - cloud platform (Huawei Cloud)", and has in-depth cooperation with BYD, BAIC and other vehicle manufacturers. Baidu integrates resources such as chips (Black Sesame), communications (China Telecom), and road-side equipment (Hikvision) with the Apollo platform as the core to form a vehicle-road collaboration ecosystem. In addition, Internet companies (Tencent, Alibaba) have entered the ecosystem through in-vehicle OS. Tencent's Auto Link TAI 4.0 has been installed in more than 3 million vehicles, realizing the integration of "content - service - travel".

The integration of AI large models and IoV has become a core trend, realizing the closed-loop optimization of "data - algorithm - decision-making". On the one hand, AI large models improve the data processing capability of IoV. For example, the automotive version of Baidu ERNIE can analyze the operation data of 100,000-level vehicles in real time to optimize the autonomous driving decision-making model. On the other hand, IoV provides massive training data for AI. Tesla's FSD system has been trained through road test data of more than 4 million vehicles worldwide, increasing the success rate of autonomous driving to 99.1%. In addition, the integration of AI and V2X realizes "predictive decision-making". For example, Huawei's MDC 910 predicts the behavior of traffic participants within 5 seconds through an AI model to avoid potential risks in advance.

Countries around the world have incorporated IoV into their strategic plans, promoting industrial development through policies and funds. China has issued the "Intelligent Connected Vehicle Roadmap 2.0", clarifying that the penetration rate of new IoV terminals will reach 95% by 2025, and more than 100 vehicle-road collaboration pilots will be built. The EU has adopted the "Digital Markets Act" to regulate IoV data security and interconnection. The U.S. Federal Communications Commission (FCC) has allocated the 5.9GHz dedicated frequency band for IoV. At the same time, infrastructure construction is accelerating. China has 20 "Dual Intelligence"

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pilot cities, and more than 5,000 kilometers of vehicle-road collaboration sections have been built, laying a foundation for large-scale application of IoV.

IoV security has been upgraded from "in-vehicle system security" to "full-link data security", covering the whole-process protection of perception data, transmission data, and application data. Technically, national secret algorithms (SM2/SM4) and TLS 1.3 protocol are adopted to ensure data transmission security. For example, Qualcomm's 9150 C-V2X chip uses the SM4 algorithm to encrypt V2X communication data. Managerially, it complies with ISO/SAE 21434 and GB/T 41871 standards, and IoV chips of enterprises such as Huawei and Horizon have passed dual-standard certification. In addition, the security emergency response system has been improved. The IoV vulnerability sharing platform built by the China Automotive Chip Industry Innovation Alliance has repaired 127 security vulnerabilities in 2024[6].

4. Core Challenges Facing IoV Industry Development

4.1. Technical Bottleneck: Dilemma of Balancing Real-Time Performance and Security

The dual demands of IoV for "low latency" and "high security" form a technical contradiction: On the one hand, autonomous driving scenarios require communication latency ≤ 1ms, which requires simplifying encryption processes. On the other hand, the risks of data leakage and hacker attacks require strengthening security protection, and complex encryption algorithms will increase latency. For example, after deploying double encryption on a domestic C-V2X chip, the communication latency increased from 0.8ms to 1.5ms, exceeding the safety standard requirements. In addition, problems such as insufficient accuracy of multi-source data fusion and insufficient generalization ability of AI models also restrict the upgrade of IoV to high-level applications.

4.2. Cost Pressure: High Costs of Both Infrastructure and Terminals

The cost pressure of IoV is reflected in two aspects: "infrastructure" and "terminals". On the infrastructure side, the construction cost of road-side equipment and edge computing nodes is 500,000-800,000 yuan per kilometer, and nationwide coverage requires trillion-level investment. On the terminal side, lidar and C-V2X modules increase vehicle manufacturing costs by 15,000-30,000 yuan, which is difficult for mid-to-low-end models to bear. Cost pressure has led to the concentration of IoV applications in high-end models. In 2024, the penetration rate of IoV in domestic models below 150,000 yuan was only 45%, which was significantly lower than the industry average.

4.3. Standard Coordination: Dilemma of Adapting International and Domestic Standards

The IoV standard system has problems of "international differences" and "domestic fragmentation": Internationally, the dispute between C-V2X and DSRC technical routes has not been completely resolved. The EU promotes C-V2X, while the U.S. still supports DSRC, forcing multinational vehicle manufacturers to adapt to dual standards. Domestically, standards in the fields of communications, automobiles, and transportation are led by different departments, resulting in conflicts in technical requirements. For example, the latency standards in the communication industry and the safety standards in the automotive industry lack coordination, increasing the compliance costs of enterprises. In addition, standards in emerging fields of AI and IoV integration (such as autonomous driving decision-making algorithms) are missing, leaving enterprises without clear basis for R&D[7].

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4.4. Talent Shortage: Insufficient Supply of Compound Talents

IoV requires compound talents with knowledge of "automotive engineering + communication technology + artificial intelligence + information security", and the current talent supply is seriously insufficient. According to data from the China Association of Automobile Manufacturers, the domestic IoV talent gap reached 80,000 in 2024, among which the gap of high-end talents with C-V2X project experience exceeded 20,000. The talent shortage has prolonged the R&D cycle of enterprises. The IoV project of a domestic vehicle manufacturer was delayed by 6 months due to the shortage of core algorithm talents.

5. Optimization Suggestions for High-Quality Development of the IoV Industry

5.1. Technical Level: Breaking Through Core Bottlenecks and Improving Integration Efficiency

Develop efficient and secure technologies: Focus on developing lightweight encryption algorithms (such as automotive-grade algorithms optimized based on SM4) to reduce latency while ensuring security, with the goal of controlling encrypted communication latency within 1ms. Promote the integration of AI and perception technologies, and develop general multi-sensor fusion algorithms to increase the environmental recognition accuracy to over 99.5%.

Build a modular technology platform: Led by industry associations, develop standardized hardware modules such as C-V2X modules and edge computing nodes, as well as software platforms such as IoV OS and data fusion algorithms, for enterprises to integrate on demand and reduce R&D costs. For example, the general IoV platform launched by the China Academy of Information and Communications Technology has been adopted by more than 20 enterprises, shortening the R&D cycle by 40%.

Layout cutting-edge technologies: Conduct early R&D on 6G and quantum security technologies. 6G can realize "space-air-ground integrated" communication to solve the IoV coverage problem in remote areas; quantum encryption technology can resist quantum computing attacks and ensure long-term data security.

5.2. Industrial Level: Building a Collaborative Ecosystem and Reducing Application Costs

Establish an industrial collaboration platform: Led by the government, integrate resources from chip enterprises (Huawei, Qualcomm), communication operators (China Mobile), vehicle manufacturers (BYD, Tesla), and transportation departments to establish an "IoV Industry Collaboration Alliance" to share road-side equipment data, vulnerability information, and technical achievements, and realize resource reuse.

Optimize the cost-sharing mechanism: Adopt a cost-sharing model of "government subsidies + enterprise co-construction + user payment". The government provides 30%-50% subsidies for vehicle-road collaboration infrastructure. Enterprises recover costs through the "hardware + service" profit model. For example, Tesla compensates for terminal costs through in-vehicle service subscription fees.

Promote large-scale application: Prioritize the promotion of IoV applications in closed scenarios such as ports, mining areas, and industrial parks, and reduce unit costs through large-scale application; gradually expand to urban roads, and achieve 100% IoV penetration in closed scenarios and 30% in urban roads by 2025.

5.3. Policy Level: Improving the Standard System and Strengthening Talent Support

Unify the standard system: Establish a national IoV standard committee to integrate standards in the fields of communications, automobiles, and transportation, and promote the mutual recognition of domestic standards and international standards (such as the EU C-V2X standard). Accelerate the formulation of special standards for the integration of AI and IoV, and clarify requirements for algorithm security and data annotation.

Increase policy support: Set up a special IoV fund to provide financial support for core technology R&D and infrastructure construction. Include IoV in the "first set (set)" policy scope, and provide tax incentives for vehicle manufacturers that adopt domestic IoV chips.

Strengthen talent training: Promote universities to set up interdisciplinary majors in "IoV Engineering", offering core courses such as automotive electronics, communication principles, and AI algorithms. Establish "school-enterprise joint training bases", with enterprises providing internships and technical guidance to cultivate compound talents in a targeted manner[8].

6. Conclusion and Prospects

Through the systematic sorting of the technology forms and industrial trends of IoV, this paper draws the following conclusions: First, IoV has formed a three-level technical architecture of "Perception - Network - Application". 5G-A and V2X are the current core communication technologies, and AI integration promotes the evolution of technology forms to "global intelligence". Second, the global IoV industry scale is expanding rapidly, and China has become a core growth pole. The industrial ecosystem is reconstructed from a "linear chain" to "networked collaboration". Third, technical bottlenecks, cost pressures, inconsistent standards, and talent shortages are the current core challenges, which need to be solved through joint efforts in technological breakthroughs, industrial collaboration, and policy support. Fourth, China has established the basic capabilities of IoV technology and industry, and domestic chips and solutions are gradually realizing substitution, laying a foundation for industrial independence and controllability.

From 2025 to 2030, IoV will enter a new stage of "global collaboration and intelligent autonomy". Technically, 6G and quantum security technologies will be gradually implemented, enabling IoV to achieve "seamless coverage" and "absolute security". Industrially, Chinese standards will achieve mutual recognition with international standards, and the global market share of domestic IoV chips will increase to more than 30%. Application-wise, IoV will be deeply integrated with intelligent transportation and smart cities, realizing the vision of "vehicle-road collaborative autonomous driving" and "zero traffic congestion". As the core of the intelligent connected vehicle industry, IoV will become an important carrier for the integration of the digital economy and the real economy, providing core support for China's automotive industry to achieve "overtaking on a curve".

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