The status, challenges, and trends: an interpretation of technology roadmap of intelligent and connected vehicles in China (2020)

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Abstract

Purpose – The rapid development of Intelligent and Connected Vehicles (ICVs) has boomed a new round of global technological and industrial revolution in recent decades. The Technology Roadmap of Intelligent and Connected Vehicles (2020) comprehensively analyzes the technical architecture, research status and future trends of ICVs. The methodology that supports the roadmap should get studied.

Design/methodology/approach – This paper interprets the roadmap from the aspects of strategic significance, technical content and characteristics of the roadmap, and evaluates the impact of the roadmap on researchers, industries and international strategies.

Findings – The technical architecture of ICVs as the "three rows and two columns" structure is studied, the methodology that supported the roadmap is explained with a case study and the influence of key technologies with proposed development routes is analyzed.

Originality/value – This paper could help researchers understand both thoughts and methodologies behind the technology roadmap of ICVs.

Keywords Technology roadmap, ICVs, Influence analysis

Paper type Viewpoint

1. Introduction

Characterized by intelligence and connectivity, a new round of global technological and industrial revolution is booming nowadays. The rapid development of Intelligent and Connected Vehicles (ICVs) has been drawing great attention. ICVs are equipped with advanced onboard sensors, controllers, actuators and other devices, and integrated with the communication network, artificial intelligence and other technologies to realize information exchange between vehicles and X (vehicles, roads, pedestrians, clouds, etc.). ICVs are closely integrated with the transportation system, energy system, city functioning and social life, which is a national-level system project integrating smart city, transportation and services (Li *et al.*, 2020; Li *et al.*, 2017). The development of ICVs is not only the trend in the field of automotive but also the general trend of the whole industry. It also plays an important role in technical breakthroughs and being the foundation of a future innovative society.

The *Technology Roadmap of Intelligent and Connected Vehicles (2020)* integrates the wisdom of top experts from China. It makes a detailed overview of the global ICV development and makes a targeted comparison of the development status of various countries according to the key technologies. It is an important research achievement of the international automotive industry. Since China has the largest market in the world, the development routes of important technologies, such as ICVs, deserve continuous attention.

There already exists some research on the development of specific ICV technology (He *et al.*, 2019), and communication

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infrastructure technology, such as 5G (Samdanis and Taleb, 2020) and 6G (Letaief *et al.*, 2019). However, few researchers focus on the overall design of ICVs and the supporting infrastructures. In this paper, the *Technology Roadmap of Intelligent and Connected Vehicles (2020)* is interpreted in ICVs' status, challenges and trends. In Section 2, the strategic significance and featured content of the roadmap are explained in detail. Section 3 focuses on who the roadmap influences: the researchers, industrial and international cooperation. Section 4 concludes the interpretation of the roadmap.

2. Interpretation of the technology roadmap

2.1 Interpretation of technology contents

ICVs include two technical aspects: intelligence and connectivity, which also classify the ICV technology correspondingly. In terms of intelligence, organizations, such as the US SAE (SAE International, 2014), NHTSA (Colwell, *et al.*, 2018), German VDA (Yu and Kang, 2016) and China Automobile Standards Committee have already given their classification schemes. Taking into account the complexity of China's characteristic road traffic conditions, the intelligent classification of this version of the roadmap adds the designed operation range (Operational Design Domain, ODD (Fraedrich, *et al.*, 2016), as shown in Table 1. As for network connectivity, according to the different communication content and the supported level of vehicle driving automation functions, it is divided into three levels: connected assistance information interaction, connected cooperative perception and connected cooperative decision-making and control, as shown in Table 2.

ICVs involve technologies in multiple fields, such as automobiles, communications and transportation. The overall technical architecture can be divided into a "three rows and two columns" structure. "Three rows" refers to the vehicle technologies, the information interaction technologies and basic support technologies involved in ICVs. "Two columns" refers to the on-board platforms and infrastructure supporting the development of ICVs, as shown in Figure 1.

In terms of vehicular technology, environment perception involves different types of sensors, e.g. camera, millimeter-wave radar, LIDAR and ultrasonic radar, etc. Except for the multi-object detection and tracking algorithm, multi-sensor data fusion and C-V2X-based cooperative perception algorithms are also of great importance. Nowadays, decision-making mainly applies rule-based method and basic AI algorithm, e.g. finite-state machine, decision tree model, etc. Further decision-making development will be focused on reinforcement learning technology and vehicle-road-cloud fused decision-making technology. Vehicle controller and actuator development will focus on X (driving, steering, braking, etc.)-by-wire and redundancy control technology. The vehicle on-board system will be gradually upgraded to an Ethernet-based, topology-simplified, AUTOSAR-standard network. The further deployment of domain controllers will also reduce the controller amount.

As for information interaction, the establishment and implementation of LTE-V2X lower the latency and improve the V2X reliability. 5G-V2X also enables ultra-reliable and low latency communication to offer customized network transmission ability for ICVs. Based on the development of network technology, roadside units can provide ICVs traffic information like traffic light signal, traffic signs, accident, traffic jam, etc. Furthermore, the integration of these technologies helps to improve the intelligent level of the road system.

Basic support technology involves various aspects. Artificial intelligence development is one of the fundamental technologies, which has extensive applications in image data processing, cloud data clustering and decision-making. The current difficulties in AI deployment are that the generalization ability and robustness of the algorithms are still bounded by the training data, which makes it hard to be used in particular weather conditions (storm, rain, snow) and unstructured road scenarios. With wider applications of autonomous functions, a Policy Protection Detection Response-based defense technology should be designed in case of malicious attack. HD mapping and localization's accuracy should be improved to decimeter or centimeter level to meet the control requirements of ICV applications. What's more, a testing and assessment database should be established based on typical traffic scenarios of China. Model in the loop, hardware in the loop and vehicle in the loop needs to be applied to cover all the traffic scenarios. Standards and regulations should also be established correspondingly.

2.2 Analysis methodology

The most substantial contribution of the roadmap is the section on the ICV technologies. In the roadmap, the ICV technology development is firstly planned in three main areas: vehicular technology, information interaction and basic support technology, as shown in Figure 1. Then, the technology roadmap of 16 technical sub-areas is explained in detail.

Guided by ISO 42010 "Systems and software engineering – Architecture description" (Emery and Hilliard, 2009), this roadmap focuses on the overall development of the ICV system architecture and its basic support technologies. In every technical sub-area, the expected goals and corresponding technical targets are first set. Second, after careful technical research and literature review, the roadmap compares the

Table 1 Intelligence level classification

Level	Intelligence classification	Control	Condition monitoring	Malfunction dealing	ODD
1	Driver Assistance, DA	Driver and System	Driver	Driver	Limited
2	Partial Automation, PA	System	Driver	Driver	Limited
3	Conditional Automation, CA	System	System	Driver	Limited
4	High Automation, HA	System	System	System	Limited
5	Full Automation, FA	System	System	System	Not limited

Table 2 Connectivity level classification

Level	Connectivity classification	Typical information	Control
1	Connected assistance information interaction	Map, traffic flow, traffic signal, fuel consumption, etc.	Driver
2	Connected cooperative perception	Vehicle, pedestrian, nonmotor vehicle, traffic signal, etc.	Driver/system
3	Connected cooperative decision-making and control	Vehicle to vehicle, vehicle to infrastructure and vehicle to cloud cooperative perception, decision-making and control	Driver/system

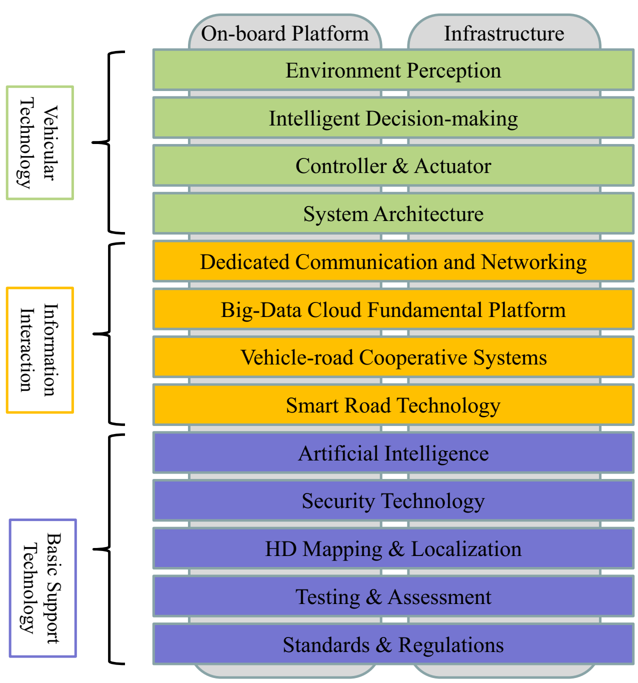
technology gap between domestic and foreign development. Third, based on the existing technical gap, the implementation route of sub-area technologies is proposed. The final technical roadmap is summarized based on the analysis above.

Take the *Big-Data Cloud Fundamental Platform*, which is the key supporting platform as well as the most representative technology road of the ICVs development in China, as an example, technical targets are firstly designed. Considering the different requirements of the three development stages, specific targets are set for a different period, among which the time delay of perception and communication is an important indicator. Corresponding technical targets are set based on theoretical analysis and experiment, here we demonstrate an example of ICV longitudinal control.

To study the effect of a time delay on vehicle control, a simulation experiment could be conducted based on car-following scenario, where a leading vehicle sends its velocity and position to the following vehicle, the follower then tracks the leader with a fixed headway. A linear feedback controller is designed for the follower. The discrete system dynamic is shown as:

$$x(k+1) = A_{long}\ x(k) + B_{long}\ a_{fdes} + Ga_p(k) \tag{1}$$

Figure 1 "Three rows and two columns" technical architecture of ICVs



$$a_{fdes}(k) = -K_{long}\ x(k) \tag{2}$$

With

$$x(k) = \left(\Delta d(k),\ \Delta v(k),\ a_f(k)\right)^T \tag{3}$$

$$A_{long} = \sum_{k=0}^{\infty} \frac{A_{long0}^{k}\ T^k}{k!} G \tag{4}$$

$$B_{long} = \sum_{k=0}^{\infty} \frac{A_{long0}^{k-1}\ T^k}{k!} B_{long0} \tag{5}$$

$$G = \sum_{k=0}^{\infty} \frac{A_{long0}^{k-1}\ T^k}{k!} G_0 \tag{6}$$

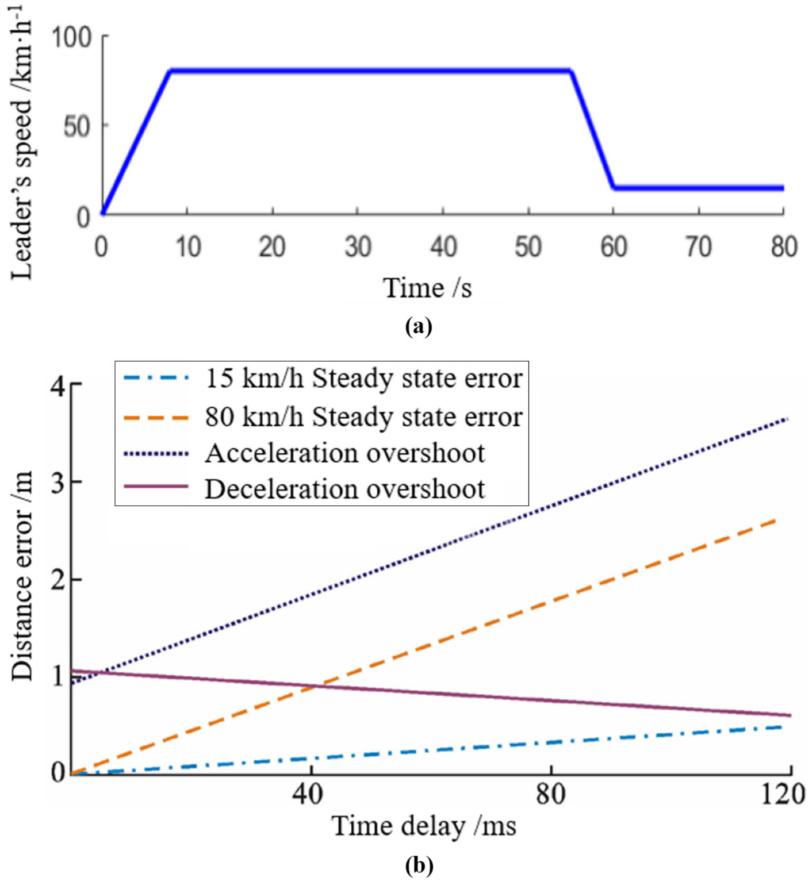
$$A_{long0} = \begin{bmatrix} 0 & 1 & -\tau_h \\ 0 & 0 & -1 \\ 0 & 0 & -\frac{1}{T_L} \end{bmatrix},\ B_{long0} = \begin{bmatrix} 0 \\ 0 \\ \frac{K_L}{T_L} \end{bmatrix},\ G_0 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \tag{7}$$

where A_{long}, B_{long} are the state vector matrix and control vector matrix of the follower, respectively, G is the control target input matrix, K_{long} is the linear state feedback controller's gain matrix, $\Delta d(k)$, $\Delta v(k)$, $a_f(k)$ are the headway error, speed error and follower's acceleration, respectively, $a_{fdes}(k)$ are the follower's expected acceleration, $a_p(k)$ is the leader's acceleration, τ_h is the time-to-collision, K_L and T_L are the acceleration's first-order gain and time constant, respectively.

The simulation is then conducted with a pre-defined leading vehicle's speed profile [as shown in Figure 2(a)], and the headway is set as $10m$. To study the time delay of perception and communication, we simulate the car-following process based on different time delay setups of the leader to send followers its speed and position information. The simulation result is shown in Figure 2(b).

As is demonstrated in Figure 2, the steady-state error and acceleration overshoot increase with the increase of time delay, and also increase with a higher vehicle speed. According to our simulation scenario, a time delay of 80 ms lead to a 1.8 m steady-state error at 80 km/h and 2.8 m acceleration overshoot. During the first research period, we set the limit of 2 m and 3 m for the two indicators, and thus generate a total time delay limit of 80 ms, which is then divided as 20 ms of upload/download communication, 30 ms of computation and 10 ms of jitter. Further studies are also conducted considering different scenarios and lateral control functions such as lane-

Figure 2 Simulation result of car-following control



keeping. The limits of time delay in the roadmap are then designed, considering the application requirements during the different development period.

As for the analysis of technology gaps in the field of *Big-Data Cloud Fundamental Platform*, between the current situation and the expected future, the roadmap gets the conclusion through the following steps:

- *Demand analysis*. The necessity of development is firstly analyzed. Since the cloud control platform can provide ICVs with better capability of centralized computing and global optimization, which will be an ideal solution to the traffic efficiency and energy economy, the development is of great importance and necessity.
- *Investigation of current technology*. The roadmap carries out a detailed investigation and analysis of the existing vehicle-road-cloud integration technology and concludes the main gaps between the existing technology and the expectation.
- *Case analysis*. Through the specific analysis of the actual implementation cases, more problems of engineering applications are exposed.

According to the main gaps obtained from the process above, the roadmap obtains several key problems that need to be solved urgently through comprehensive comparison. The urgency analysis process is shown in Table 3, where S1 represents the expected development level, S2 represents the current development level and S3 represents the fundamentality level of a technology item.

As for the implementation route, the roadmap determines the priority of technology implementation by comprehensively comparing development demands and technology gaps. In the field of the cloud control platform, the technology is expected to be realized through the following four steps:

- *Standard setting*. Complete vehicle-road-cloud data acquisition standards, platform architecture standards and related technical standards need to be developed in priority to ensure that the data of different manufacturers can be quickly accessed to the platform and processed to reduce redundant work.
- *Infrastructure development*. Second, edge computing technology of multi-access needs to be developed. This will promote cooperation among operators, management departments and equipment suppliers, and solve common basic problems through testing.
- *Cloud fusion*. Then, we need to vigorously develop the end cloud fusion technology to solve the main technical problems of single-vehicle automatic driving and intelligent transportation.
- *Construction of edge-cloud architecture*. Through the construction of hierarchical cloud control system architecture, the global data management in large scope and real-time data carding work in small scope are solved, respectively, which will effectively support the realization of perception, decision-making and control technology of ICVs.

According to the case study relating to the Big-Data Cloud Fundamental Platform, main aspects are analyzed, including

Table 3 Urgency analysis of the main gaps

Technology item	S1 (1–5): expected development score	S2 (1–5): current development score	S3 (1–5): fundamentality score	Comprehensive score (S1−S2+S3)
Data standards	5	1	5	9
Perception accuracy	5	3	4	6
Communication quality	5	3	4	6
Evaluation criterion	5	2	3	6

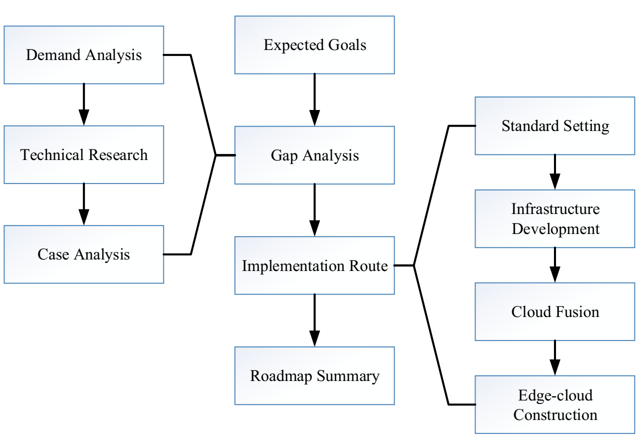
technical targets, technology gap as well as implementation path, the roadmap is finally generated as a summary and guidance for the society to refer to. And a similar analysis methodology is applied to other sub-area technologies (as shown in Figure 3). In general, scientific and practical roadmap is obtained.

2.3 Features of the technology roadmap

The first version of the technology roadmap (China, SAE, 2016) proposed a comprehensive technical framework of ICVs for the first time in the world. It refers to the relevant technical standards proposed by Europe, the USA and Japan, and is closely combined with the actual characteristics of the development of ICVs in China. After several years of modification and updating, the current version of the technology roadmap is more authoritative with being reviewed and revised by experts in the automotive industry. Compared with the existing technical standards and development plans of other countries, the current version of the technology roadmap has the following characteristics:

- In terms of technical content, the development status and future technology route of key technologies related to ICVs are comprehensively analyzed. For each key technology, the technology roadmap analyzes its expected goals, the gap compared with current technologies of other countries, the implementation path and the roadmap. Besides, the technology roadmap revises the technical architecture and system of ICVs. For example, system design technology is added to the key technology part of the vehicle, including electronic and electrical architecture, human-machine interaction and AI-based computing platform.
- In terms of concept and architecture, the technology roadmap proposed the connectivity classification standards for the first time in the world, which is referred to later-published standards of other countries, like the "ISAD levels." Besides, the technology roadmap integrates the concept of "smart car" and "smart road," which has become an industry consensus. With the development of 5G communication technology, the intelligent infrastructure has more powerful abilities for environment perception and edge computing, which makes the infrastructure able to cooperate with vehicles to perform coordinated perception, decision-making and control, and to coordinately support the realization of automatic driving.
- In terms of the promotion of industrialization, the technology roadmap extends the research targets to the year 2035, with 2025, 2030 and 2035 as milestones. For example, the industrialization goals of ICVs are divided into three stages: the development period (2020–2025), the promotion period (2026–2030) and the maturity period (2031–2035). The technology roadmap also studies the implementation and development trend of industrialization of intelligent and connected technologies of passenger vehicles, freight vehicles and passenger vehicles, mainly analyzing the schedule of technology industrialization, marketization and commercialization of ICVs within urban roads, suburban roads, highways and limited scenarios.
- In terms of Chinese characteristic content, ICV development is involved with multiple domestic industries, such as automobiles, transportation and information and communications. Communication, maps and data are of great importance to national security, thus need unified national-level supervision, which also means that the foreign development path cannot be copied directly. Chinese characteristic route will adhere to full integration of intelligence and connectivity and will use five fundamental platforms as the development carrier: on-board computing platform, smart terminal platform, cloud control platform, HD dynamic map platform and information security platform. Some of the key technologies are shown in Table 4.

Figure 3 Roadmap analysis methodology



2.4 Strategic significance

The technology roadmap explains the significance of the development of ICVs. As a combination of the automobile, information, communications, artificial intelligence and other technologies, ICVs directly promote a new round of revolution in science, technology and the automobile industry. At present, Europe, the USA and Japan have strong advantages in specific fields of ICVs' technology. China needs to accelerate the innovation and development of ICVs. The roadmap describes the strategic significance of the development of ICVs for China from three aspects: economic, social and comprehensive national strength development.

- The development of ICVs builds a new economic growth trend. In the era of intelligence, ICVs are the application platform of artificial intelligence, mobile internet, information

Table 4 Five fundamental platforms

Fundamental Platforms	Key technologies
On-board computing platform	Low-energy high-performance microchip, parallel computing
Smart terminal platform	Controller and actuator design, smart road technology, HMI design
Cloud control platform	Intelligent decision-making, Big-data cloud processing, vehicle-road cooperative systems
HD dynamic map platform	Environment perception, HD mapping and localization, simultaneous localization and mapping
Information security platform	Dedicated communication and networking, security technology

technology, cloud computing, renewable energy and multiple technologies. The application of those new technologies, on one hand, breaks the conventional industry chain and technology chain of the automobile industry and provide a big opportunity for China's automobile industry. On the other hand, it promotes innovation, breakthroughs and industrialization of new technologies. It also drives the upgrade, iteration and integration of related industries.

- The development of ICVs helps to build a smart city and society. With the continuous improvement of the intelligent level of vehicles, the vehicle is changing from a simple tool of transportation to an intelligent mobile terminal and becomes an important part of a smart city. ICVs strengthen the connection and coordination among the vehicle, road-side infrastructure and users, help to form a safe, efficient and energy-saving intelligent transportation system. Besides, ICVs will gradually replace human drivers, which will not only provide support for shared travel services but also will effectively solve the mobility problems for senior people.
- The development of ICVs enhances the national strength of China. The difficulties with ICV technology make it a symbol of national scientific-technical advancement, and the potential market demand for ICVs could provide financial support, as well as application scenarios, to promote the research into scientific fields of computer science, basic mathematics, IC-design, etc. ICVs constantly generate and collect multiple kinds of valuable data, which will become strategic resource in the era of intelligence. The development of independent and transparent ICVs' technologies, thus also has significant meaning to national security.

3. Influence analysis

3.1 Influence on the academia

ICVs have been risen to China's national development strategy. The roadmap points out the research directions and priorities for researchers directly engaged in related areas. For other researchers who is not directly-related, it can deepen their understanding of the development trend of Chinese ICV as well as automobile industry. In detail, the influence on academia can be summarized as follows:

- The technology roadmap provides researchers with more instructive research directions. There are many different ICV technical roadmaps around the world, such as the USA's CARMA project (US Department of Transportation Federal Highway Administration, 2020), Germany's Ko-HAF project (Andree, 2020) and EU's 5GCAR project (Fernandez *et al.*, 2017). The roadmap complies with its characteristics in China and points out the key technologies of each stage of China's ICV domain.
- The research progress of ICV is a long-term and complex project. Researchers need to consider both the near-future technology and the more forward technology, such as 6G for ICVs (Tang *et al.*, 2019). In addition to directly-related researchers, researchers from other fields or basic science have a better understanding of China's ICV policy and potential future demands.
- The roadmap clarifies the respective responsibilities, as well as priorities for the industry and academia at all stages, which can promote better integration of industry, university and research.

3.2 Influence on the industry

The technical roadmap has conducted an in-depth analysis of the current development stage of ICVs, analyzed the current industry status of ICVs and pointed out that ICV-related industries own a very promising future. The influence on the industry can be summarized as follows:

- The technology roadmap plays an important guiding role for OEMs and other related companies. It can help these companies deeply analyze the future market's demand for new products and technologies for ICVs. It clarifies the key and fundamental technologies that need to be broken through at the same time.
- Similar to academia, the technology roadmap clearly defines the key technologies of various companies in various industries under the overall strategy of automotive and helps companies to better establish technology barriers under the new situation and command.
- The technology roadmap helps the technical specifications of related sub-fields to be implemented as soon as possible and accelerates the establishment of ICVs' standard and specification system, such as interface standard of cloud control. Based on these standards, more effective cooperation will be guaranteed between upstream and downstream industries.

3.3 International influence

The technology roadmap indicates Chinese explorations as well as characteristics of the global development of intelligent road transportation. Chinese achievements of ICV technology have drawn global attention. The International influence of this roadmap is summarized as follows:

- The roadmap provides an important reference for global ICV researchers in terms of standard-setting and market strategy. As a pioneer of ICVs, China published the world's first guidance document for the construction of ICV industry, "Roadmap of Intelligent and Connected Vehicle (2016)" (Ministry of Industry and Information Technology of China, 2016), which is then followed by a set of specifications for functional tests and road tests. While the EU conducted its 5G-CAR (Fernandez *et al.*, 2017) research from 2017 to 2019, the Chinese documents were the main references for this project. "ISAD levels," published with EU Connected Automated Driving Roadmap in 2019 (ERTRAC Working Group, 2019), applied the same connectivity classification standards as the Chinese roadmap in 2016. Besides, as the world's largest automobile production and consumption country, China owns a large potential market for ICV-related equipment and service. Global suppliers have been studying Chinese demands, and this roadmap will be the latest and most important reference.

- To support the development of Chinese ICV, and prepare for the future global competition, the roadmap instructs opportunities, as well as tasks for Chinese industry, research and government. From the perspective of the three-period ICV development steps (development, promotion and maturity), China should develop core technologies and abilities for collaborative innovation, forming a healthy industrial ecology and participate in international competition with our leading enterprises. To reach these targets, this roadmap proposes three main strategies: stick to the development path with Chinese characteristics and take the advantages of our leading industries and governing system; take the historical opportunity of industry transformation and promote the research of automotive software; strengthen the research relating to safety technology of ICV, which should be the core value among every aspect of ICV development.

4. Conclusions

Technology Roadmap of Intelligent and Connected Vehicles (2020) points out the key technologies and development routes of ICVs in the next 15 years. First, it defines the classification of intelligence level and connectivity level of ICVs. Second, it describes the technical architecture of ICVs as the "three rows and two columns" structure. Third, it analyzes the shortcomings of different key technologies and proposes the corresponding development routes. The roadmap has brought about a positive impact on academia, industry and international strategy, and greatly promoted the development of ICVs all over the world.

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