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How Does China Explore the Synergetic Development of Automotive Industry and Semiconductor Industry with the Opportunity for Industrial Transformation?

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Abstract: Amidst the unfolding technological revolution and industrial transformation, the synergistic development between China's automotive and semiconductor industries has emerged as a salient trend. To explore the potential difficulties and pathways of the synergistic development of the two industries, this study conducted cross-sectional surveys across three phases, specifically in March 2021, March 2022, and March 2024. The first phase of the survey identified that the two industries could mutually promote each other in both technical and market aspects and pinpointed three major challenges: computational capacity bottlenecks, supply chain risks, and unclear industrial cooperation models. The second phase of the survey discussed three opportunities to address the three challenges, respectively: intelligent vehicle infrastructure cooperative system, supply chain localization, and the reconstruction of the technology stack. The third phase of the survey summarized the development experience over the past three years, validated the aforementioned opportunities, and suggested the government promote the digitalization of vehicles and mobility, automotive companies use more domestic chips, and two industries build the ecological cooperation model.

Keywords: automotive industry; semiconductor industry; industrial transformation; China; synergetic development; industry chain sustainability

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1. Introduction

In today's world, the automotive industry and semiconductor industry are regarded as strategic industries by major countries such as the United States, China, Japan, South Korea, and Germany [1]. The automotive industry, as a carrier industry that embodies the culmination of human technology, holds immense potential for technological innovation [2]. Faced with waves of intelligence, connectivity, and electrification, the automotive industry is undergoing a revolutionary transformation [3]. China's automotive industry, with its rapid development momentum, has become a main leader in global industrial restructuring [4]. Meanwhile, the semiconductor industry, as a foundational industry of the digital era, is rapidly expanding in various application scenarios and markets [5]. However, due to a late start and conflicts in international politics, China's semiconductor industry still faces numerous challenges such as technological blockades [6]. Therefore, synergistic development has become an important strategic choice for the Chinese automotive industry and semiconductor industry.

In the new wave of industrial transformation, the automotive industry and semiconductor industry are showing a trend of cross-industry collaboration. On one hand, an increasing number of semiconductor companies are entering the automotive business and making it a core area of development [7]. On the other hand, automotive companies are emphasizing semiconductor technology and supply chains, even actively engaging in semiconductor design and manufacturing [8]. Automotive semiconductors serve as a key enabler for mutual empowerment, becoming a crucial element for the synergistic development of these two industries. However, it is important to recognize that automotive semiconductors may also become a bottleneck that limits the development of China's automotive industry [9]. From late 2020 to 2022, the automotive industry experienced a chip shortage, severely impacting automotive production and sales [10]. Therefore, the implementation of a strategy for synergistic development between the two industries is of vital importance for China. The synergistic development of the two industries is an inevitable trend and a key factor in achieving industrial upgrading and global competitive advantage.

In previous studies, the automotive industry and semiconductor industry have often been treated as separate research subjects, focusing on specific technological research and applications of automotive semiconductors. Frieske et al. [11] discussed how original equipment manufacturers (OEMs) can improve the resilience and risk management of semiconductor supply chains in the context of chip shortages, highlighting digitalization as a key approach. Ahmad [12] presented the industry development trends of automotive semiconductors from the perspective of technological advancements, analyzing the impact of integrated circuit miniaturization on automotive technology architecture. Nam et al. [13] utilized patent analysis techniques to identify the main technological development paths of automotive semiconductors, finding that both the convergence and independence of automotive semiconductor technology proceeded simultaneously. Shinojima [14] discussed the new demands for semiconductors driven by the trends Connected, Autonomous, Sharing and Service, and Electric (CASE) in the automotive industry. There has been a paucity of strategic research conducted at the level of synergistic development between the two industries. This lack of holistic perspective fails to capture the complex interdependencies. While some research has touched upon the current state of the relationship between the two industries, long-term historical analyses of their co-development trajectories are scarce. Understanding how the symbiotic relationship has evolved over time is crucial for predicting future trends. Without this historical context, it is difficult to accurately anticipate the potential directions of their synergistic development, especially in the face of rapid technological disruptions. As a result, there is a lack of systematic and clear combing on how to improve the sustainability of the automotive semiconductor industry chain. The purpose of this paper is to comprehensively analyze the strategic value of automotive semiconductors, identify key challenges and opportunities in their development process, and explore strategies for promoting the synergistic development of the two industries. To achieve our objectives, we have formulated the following research questions:

RQ1. *What is the value of the automotive industry and semiconductor industry to each other in China?*

RQ2. *What are the key challenges faced by China in achieving the synergistic development of the two industries?*

RQ3. *What opportunities during the industrial transformation process can China leverage to address the key challenges?*

By conducting an in-depth analysis and discussion of these three questions, we aim to provide new insights and strategic pathways for the synergistic development of the two industries. By strengthening cooperation and innovation between these two strategic industries, we can provide valuable recommendations for China to maintain a leading position in both sectors, thereby injecting new momentum into the sustainable development of the Chinese economy and enhancing the overall competitiveness of the nation [15]. The remainder of this study is organized as follows. Section 2 provides an overview of the research methodology. Sections 3–6 present and explain our research findings. Finally, Section 7 concludes the paper.

2. Methodology

This study conducted a cross-sectional analysis at three different time points. Since the end of 2020, the chip shortage has gradually spread to the global automotive supply chain. Our team quickly identified the research topic and began to consider the research approach, successfully organizing an expert seminar in March 2021 to gather insights and answers related to RQ1 and RQ2. The second time point was in March 2022, providing the industry with one year of reflection time. We then conducted exploratory semi-structured interviews with specific experts to address the identified challenges and extract opportunities and development pathways that can help address these challenges during the industrial transformation process, thus answering RQ3. The participants in this stage included both members of the expert seminar and new professionals. The third time point was in March 2024 when we reviewed the achievements made by China in automotive semiconductors after a two-year interval. We selected some cases to analyze whether the opportunities identified and development pathways proposed two years earlier were effective. Additionally, we summarized practical experiences and provided recommendations for further synergistic development in the future. By employing this three-time-point analysis approach, we aimed to capture a comprehensive understanding of the strategic value, challenges, and opportunities in the synergistic development of the automotive industry and semiconductor industry in China.

2.1. Expert Seminar

The expert seminar is a qualitative research method that involves inviting experts with rich experience and professional knowledge to engage in in-depth discussions and exchanges in order to obtain professional insights and perspectives on the research questions [16]. For RQ1 and RQ2, we invited eight top industry experts to participate in the workshop. We ensured that these experts had at least 10 years of working experience in the automotive and semiconductor industries and represented various stakeholders. Their influence within the industry allowed them to have a broad view of the strategic initiatives, partnerships, and competitive landscapes. Additionally, their extensive networks could potentially provide access to a wealth of unpublicized information and emerging trends. The participating experts include:

- One university professor: possessing a deep understanding of the development trends and academic research experience in the automotive and semiconductor industries;
- Two OEM executives: as senior executives of automotive manufacturers, they can provide internal perspectives on the industry and insights into strategic decision-making;
- One founder of an automotive semiconductor startup: representing an emerging automotive semiconductor company and able to share entrepreneurial experiences and views on the future development of the industry;
- One executive from a major automotive semiconductor giant: from a prominent company in the automotive semiconductor field, able to provide industry leadership insights and strategic perspectives;

- Two executives from tier-one automotive component suppliers: representing the interests of suppliers and providing in-depth understanding of supply chains and cooperative relationships;
- One automotive semiconductor investor: as an investor, able to provide observations and analysis of industry investment trends and business opportunities.

By selecting such a diverse group of experts, we were able to obtain perspectives from different fields and stakeholders, thereby gaining a deeper understanding of the interrelationship between the two industries.

To ensure the effective progress of the seminar, we developed a detailed agenda to facilitate thorough discussions on the research questions within the limited time. For RQ1, the participating experts primarily discussed the interrelationship between the two industries, exploring their mutual value and potential cooperation opportunities. For RQ2, the participating experts jointly analyzed and discussed the key challenges faced by China in achieving synergistic development of the two industries, including challenges in technology, supply chains, and industry cooperation. The design of the seminar agenda aims to promote interaction and knowledge exchange among the participating experts in order to obtain comprehensive and in-depth insights.

During the seminar, we employed various data collection methods, including audio recording and note-taking, to ensure accurate documentation of the discussions. The data analysis adopts a qualitative analysis method. We carefully listened to the seminar recordings and read through the notes to familiarize ourselves with the experts' perspectives and the content of the discussions. The results of the seminar will be presented in Sections 4 and 5, including an in-depth analysis of the key values and challenges for the synergistic development of the two industries.

2.2. Semi-Structured Interview

A semi-structured interview is a method that allows for an in-depth understanding of interviewees' viewpoints, experiences, attitudes, beliefs, and their understanding of specific topics or research areas [17]. Compared to fully structured interviews, semi-structured interviews provide more flexibility, enabling interviewees to freely express their opinions and provide detailed information when answering questions [18].

To gain more insights and perspectives, we expanded the range of research experts and selected different interviewees based on the topic. For technical topics, we primarily interviewed research and development managers from relevant companies, as well as researchers from universities and research institutions who possess professional knowledge and experience in the technical field. For supply chain topics, we mainly interviewed supply chain managers and procurement managers from OEMs, as well as executives from suppliers. For industry collaboration topics, we primarily interviewed strategic decision-makers from relevant companies, professional investors, and some grassroots employees to obtain opinions from different levels and perspectives. By selecting interviewees from different fields and levels, we were able to obtain diverse viewpoints and experiences, thus gaining a more comprehensive understanding of the opportunities in the synergistic development of the two industries.

The design of semi-structured interviews is based on exploratory and open-ended principles [19]. We developed an interview guide that includes some open-ended questions and topics to guide the interviews but also allows for enough space for interviewees to freely express their opinions and provide in-depth insights. The content of the interview guide was adjusted and personalized for different topics. For technical topics, our questions covered areas such as technology development trends and technological innovation. For supply chain topics, our questions covered areas such as supply chain management practices, the optimization of supply relationships, and risk management. For industry collaboration topics, our questions covered areas such as collaboration models, resource sharing, collaboration barriers, and successful case studies.

Interviews were conducted face-to-face or by phone and ranged in duration from 30 to 85 min. The sample consisted of 32 h of interviews. We will cite the viewpoints and experiences of the interviewees in an anonymous manner in this paper to protect their privacy. In addition, we will conduct a comprehensive analysis of the interview results and compare and discuss them with the research findings from the other literature. This will help us gain a deeper understanding of the opportunities in the industry transformation process and provide relevant recommendations.

2.3. Multiple Case Analysis

In this study, we also employed a multiple case analysis method to validate the development pathways derived from the semi-structured interviews. On the one hand, this method allows us to extract lessons from successful cases to provide reference and guidance for other companies. On the other hand, it enables us to validate the initial recommendations after a certain period of time and make necessary adjustments and modifications to ensure the industry is on the right track.

We selected a series of representative and diverse practical cases for our research. These cases may involve collaborative projects, technological innovations, supply chain optimization, and other aspects in the automotive and semiconductor industries. We conducted extensive searches within the industry, both internally and externally, to gather these cases and select them based on their relevance to the research topic. This approach provides a more comprehensive and multi-dimensional perspective, enriching the content and quality of the research. For each selected case, we collected relevant literature, reports, news articles, and official public information to obtain detailed case descriptions and related data. Additionally, we made efforts to contact relevant companies or individuals for in-depth interviews or to gather supplementary information. By comparing and contrasting the differences and similarities among different cases, we are able to draw conclusions and perspectives on the development pathways. Furthermore, we will integrate the results from the semi-structured interviews and literature review to conduct a comprehensive analysis and interpretation of the cases. This can help us gain a deeper understanding of the essential characteristics of the synergistic development between the two industries and provide feasible recommendations.

3. The Synergy Between the Automotive Industry and Semiconductor Industry

3.1. Semiconductors Support the Digital Upgrade of Automotive Industry

The first half of the competition in the automotive industry is focused on electric vehicles, while the second half is centered on intelligent vehicles [20]. Applications such as autonomous driving, intelligent cockpits, and the internet of vehicles have become increasingly important features that consumers pay attention to [21]. Digitization is the essence and prerequisite of intelligent vehicles, and semiconductors are the key foundational support for digitization [22]. As shown in Figure 1, the generation, transmission, storage, processing, and utilization of automotive data all rely on the functionality and performance of various chips. It is important to emphasize that it symbolizes the digitization of the industry, covering automotive products and all enterprise-activity aspects like R&D, design, procurement, manufacturing, sales, and operations [23].

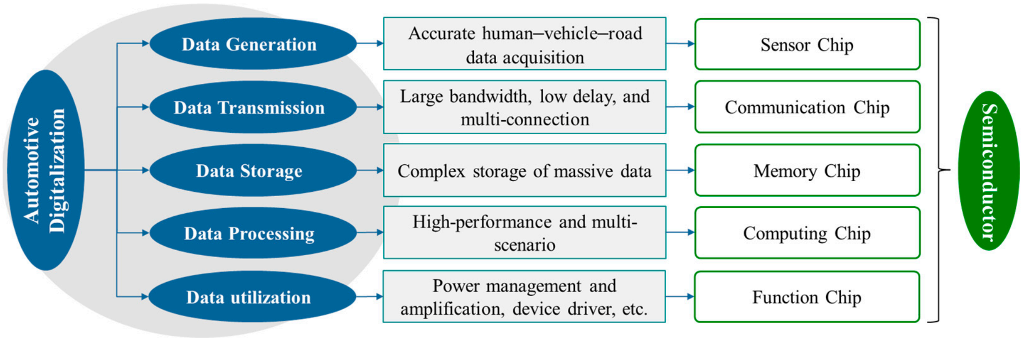

Figure 1. The demand for automotive digitalization for semiconductors.

3.2. Semiconductors Build the Technical Moat of Intelligent Vehicle

As the amount of data processed in automobiles continues to increase, the central computer, with the computing chip as its core, has become one of the most important components in intelligent vehicles [24]. The higher the computing efficiency of the central computer, the lower the cost of achieving the same functional performance [25]. Since mass-produced vehicles are highly cost-sensitive, the actual computing efficiency of the central computer directly determines the product competitiveness of intelligent vehicles [26]. The actual computing efficiency CE_A can be expressed by Formula (1):

$$CE_A = CE_{TP} * UR \quad (1)$$

CE_{TP} is the theoretical peak computational efficiency of a computing chip. UR is the effective utilization rate of computing chip resources used by automotive software. On the one hand, improving the CE_{TP} requires advanced chip design capabilities and process technology, in which China currently lacks an advantage compared to foreign companies [27]. On the other hand, different operating systems have varying efficiency in scheduling resources of the same chip, and the same algorithm may run at different speeds on different chips [28]. With the advancement of coordinated software and chip design, the UR can be optimized from 20–30% to 80–90% [29]. Therefore, if automotive computing chips can be jointly developed with automotive software tailored to China's unique scenarios and demands, there is an opportunity to create a highly competitive technical solution that serves as a technical moat for companies in the market.

3.3. The Automotive Market Enables China's Semiconductor Industry to Self-Hematopoietic

The semiconductor industry heavily emphasizes economies of scale, resulting in a few giant companies dominating the majority of market shares in each specific field [30]. Chinese semiconductor companies have relied on government subsidies for a long time due to their late start, which prevented them from enjoying cost advantages [31].

However, the Chinese automotive market is vast, with sales volumes approaching the combined total of the United States, Japan, and Germany, and it still holds tremendous potential. Conservatively estimating, there is an additional growth space of nearly tens of millions of vehicles until the peak annual sales volume is reached [32]. Simultaneously, intelligent vehicles in China are rapidly penetrating the market, with the new vehicle penetration rate of advanced driver assistance systems (ADAS) already exceeding 30% [33]. The demand for computing chips, control chips, storage chips, sensor chips, and other components is increasing rapidly due to the trend of vehicle intelligence. According to data from the China Association of Automobile Manufacturers, the average chip usage per vehicle is currently 934 for traditional vehicles and 1459 for intelligent vehicles. It is projected that by 2025, these figures will expand to 1200 and 2000, respectively [34].

Therefore, the increasing demand for chips in the automotive industry has become a strong driving force in the semiconductor industry. If Chinese semiconductor production capacity can effectively meet the needs of the domestic market, it will have the ability to break free from dependence on government subsidies and enter a positive cycle of healthy development.

3.4. Automotive Application Demand Helps China's Semiconductor Industry Overtake in Corners

The application scenarios of automotive electronics and consumer electronics such as smartphones have significant differences, and there are also notable differences between intelligent vehicles and traditional vehicles [35]. The most typical example of computing chips is shown in Table 1.

Table 1. Performance requirements of computing chips in different devices.

Performance Index	Traditional Vehicle Computing Chip	Intelligent Vehicle Computing Chip	Smart Phone Computing Chip
Computational capacity	Low	Extremely high	High
Manufacturing process	>65 nm	<28 nm	<10 nm
Software openness	HW–SW strong binding	Rich ecosystem	Rich ecosystem
Scalability	No	Yes	No
Reliability	Extremely high	Extremely high	Medium
Service life	>5 years	>5 years	~5 years
Safety	Extremely high	Extremely high	Medium

The unique requirements of intelligent vehicles for computing chips diminish the advantage of foreign incumbents, providing an opportunity for China's semiconductor industry to achieve leapfrog development. On one hand, the computing chips for intelligent vehicles need to meet both the automotive-grade requirements of traditional vehicle chips and extremely high computational capacity demands [36]. Moreover, new requirements continue to emerge, such as scalability after sale. Even major foreign chip giants cannot directly migrate their existing products for application and need to be redeveloped with specific targets in mind. On the contrary, latecomers are often more sensitive to market demands and can react more quickly, making it more likely for them to develop competitive differentiated products [37]. On the other hand, the physical space in vehicles is larger than that of consumer electronics products, and in many cases, there is no need to pursue the most advanced manufacturing processes. According to industry predictions, China has the potential to achieve independent control over 14–28 nm chips within 5 years [38], partially mitigating the risk of chip supply disruption due to trade conflicts between China and the United States. In the future, with the application of 5 nm/4 nm chips in vehicles, the development of intelligent vehicles will be conducive to the progress of smaller chips, especially in terms of balancing performance and safety.

Overall, the unique demands of intelligent vehicles and the favorable conditions in the Chinese market provide an opportunity for the Chinese semiconductor industry to develop differentiated and competitive products, leveraging its sensitivity to market demands and potential manufacturing capabilities.

4. Challenges of the Synergetic Development of Automotive Industry and Semiconductor Industry

During the expert seminar, the challenges discussed by the experts could be categorized into three main categories: technical, supply chain, and industrial cooperation.

4.1. Technical Challenges

It is expected that in the coming years, the demand for computational capacity in intelligent vehicles will continue to expand [39]. However, there are technical bottlenecks in the mass production of the central computer with ultra-high computational capacity. Currently, there are three main technical approaches to achieving ultra-high computational capacity, each with its own challenges:

- Single System-on-Chip (SoC) with ultra-high computational capacity: This approach integrates heterogeneous computing modules such as CPUs, GPUs, and NPUs into a single chip. The high level of integration creates issues like functional safety and heat dissipation complex, and it also makes the overall solution less flexible in terms of adjustments [40];
- Cascading multiple SoCs with high computational capacity: This approach involves cascading multiple SoCs with the same architecture through inter-chip communication technologies to achieve computational capacity expansion, thereby reducing the computational capacity of individual SoCs. However, this approach may suffer from significant performance losses, resulting in higher overall material costs compared to other approaches [41];
- Chiplet: This approach involves designing and manufacturing different computing modules like CPUs, GPUs, and NPUs as separate small chips (called chiplets), which are then integrated using advanced packaging technologies. Chiplets are considered an important technical approach for achieving computational advancements in the post-Moore's Law era. However, the related toolchains and developer ecosystems are not yet mature [42].

These three approaches represent different strategies for addressing the challenges of achieving ultra-high computational capacity platforms, and each has its own trade-offs and areas that require further development and improvement.

4.2. Supply Chain Challenges

From the end of 2020 to 2022, the automotive industry experienced multiple waves of chip shortage due to black swan events such as the pandemic and natural disasters, resulting in a global production reduction of over tens of millions of vehicles [43]. Through extensive discussions among experts, it was unanimously agreed that the black swan events were just surface manifestations, and the fundamental reason lies in the structural issues within the automotive chip supply chain. The specific issues identified are as follows:

- Just-in-time production mode: In the past, the automotive production management pursued zero inventory, which resulted in the absence of long-term stable supply relationships and buffer inventory for chips;
- Excessive reliance on Tier 1: OEM demands cannot be directly communicated to chip manufacturers, leading to slow supply-demand adjustment. Additionally, the high degree of concentration in the supply chain makes it difficult for OEMs to flexibly switch chips;
- Highly concentrated production capacity layout: In the past, most high-end chips in automobiles were outsourced to large contract manufacturers [44]. Once production capacity is compromised, there is no alternative capacity available;
- Mismatched production capacity planning of wafer fabs: In recent years, several major wafer fabs that supply automotive chips have gradually shifted their production capacity towards consumer chips due to profitability [45];
- Market forecasting failure: The lack of effective methods for predicting market demand has resulted in insufficient inventory;

- Trade protectionism: Countries tend to ensure local supply stability through trade restrictions, and China lacks sufficient bargaining power in the automotive chip supply chain [46].

As of today, the automotive industry has entered the "post chip shortage" era. The direct factors causing this chip shortage have gradually dissipated but the indirect impact of black swan events is showing a long-term trend. Structural issues in the automotive chip supply chain have become the main cause of chip shortages. On the supply side, investment in automotive chip production lines is large and time-consuming, while product profitability is low and the payback period is long [47]. This leads to a lack of willingness among wafer fabs to expand production, resulting in slow capacity growth. On the demand side, rapid development in intelligent electric vehicles has led to a surge in demand for automotive chips. Against the backdrop of supply shortages, the global logistics and trade of automotive chips have also been influenced by unstable international political and economic situations, as well as concerns about supply chain security triggered by black swan events [48]. This further exacerbates the risk of chip supply disruption in China's automotive industry. The consequences of the imbalance between supply and demand for automotive chips are not only reflected in reduced output but also have the potential to hinder the momentum of China's automotive industry and lose its current advantages in the global automotive industry competition. Therefore, this issue must be given high attention.

4.3. Industrial Cooperation Challenges

In the process of cross-industry collaboration between the automotive industry and semiconductor industry, it is not only important for chip companies to pay attention to the automotive business but also for OEMs to proactively establish a presence in the chip industry. Currently, there are four main strategies adopted by the industry, each with its own potential issues. OEMs need to make reasonable choices and continuously adjust and optimize their cooperation boundaries with chip companies:

- Strategic investment: This involves OEMs investing in chip startups or establishing joint ventures with chip companies. The purpose of this strategy is to secure excellent chip resources within the industry. However, chip startups themselves need to continually expand their customer channels, and the strategic investment by OEMs may not only fail to secure chip resources but also expose them to additional capital risks in the highly competitive market;
- In-house R&D: This refers to OEMs choosing to independently develop core automotive chips in-house. However, the R&D cost for an automotive AI chip with a process node below 14 nm exceeds USD 200 million [49]. OEMs face challenges in achieving cost amortization through large-scale applications, and there is also significant uncertainty in R&D;
- Co-development: This involves OEMs and chip companies establishing joint R&D teams to collaboratively design chips. However, most OEMs have a limited accumulation of chip technology knowledge, and it is unclear what specific role they can play in cooperation with chip companies. The actual contribution to improving product competitiveness remains uncertain;
- Multi-party strategic alliances: Typically led by OEMs, this strategy involves forming technical innovation alliances with multiple regional universities, research institutes, and related companies. However, this model is limited by regional constraints and is difficult to replicate and promote. Moreover, coordinating among numerous participants presents challenges, making it hard to truly form collaborative synergy.

5. Opportunities and Paths of the Synergetic Development of Automotive Industry and Semiconductor Industry

Through an integrative analysis of semi-structured interviews, this study has identified three key opportunities that correspond to three major challenges facing the synergistic development of the automotive and semiconductor industries during the period of industrial transformation and change: intelligent vehicle infrastructure cooperative systems corresponding to the computational capacity bottleneck, localization of automotive chip supply chain corresponding to supply chain toughness, and reconstruction of a technology stack corresponding to new collaboration models.

By identifying these three key opportunity–challenge pairings, this study provides some paths for industry stakeholders to strategically navigate the complex landscape of industrial transformation and leverage complementary capabilities to achieve synergistic development between the automotive and semiconductor sectors.

5.1. Intelligent Vehicle Infrastructure Cooperative System

Faced with the challenge of computational capacity bottleneck, the integration of off-board computing resources through intelligent vehicle infrastructure cooperative systems has emerged as a new strategic approach [50]. According to the planning outlined in the "Intelligent and Connected Vehicle Technology Roadmap", an intelligent vehicle infrastructure cooperative system will integrate the software and hardware resources of vehicle–road–cloud networks, gradually realizing coordinated perception, computation, and decision-making [51]. This will enable the partial offloading of sensing, computing, and storage capabilities from the vehicle end to the roadside infrastructure and cloud platforms.

An intelligent vehicle infrastructure cooperative system holds the potential to simplify the sensor and computational capacity configurations required on the vehicle, allowing for the use of less powerful onboard processors. This presents a valuable opportunity for China, where the country's leading advantages in 5G and cloud computing technologies can be leveraged to overcome the constraints of chip fabrication processes, potentially enabling an "overtaking around the bend" in this industry [52].

5.2. Localization of Automotive Semiconductor Supply Chain

Faced with the potential recurrence of automotive semiconductor shortages, the localization of the supply chain is widely regarded as the optimal choice to enhance supply chain resilience [53]. Firstly, localization can help reduce the geographical distance and complexity of the supply chain, shortening the transmission time of information flows and logistics, thereby mitigating the impact of geopolitical uncertainties and natural disasters and improving response speed and adaptive capacity. Secondly, localization can enhance the transparency of information and the level of collaboration within the supply chain, facilitating high-degree coordination among different supply chain segments and strengthening risk warning and response capabilities. Moreover, localization not only reduces reliance on international logistics but also increases the flexibility and optimization potential of resource allocation, thereby improving the efficiency of supply chain resource utilization [54]. Finally, localization can strengthen policy support and regulatory oversight, enabling the government to provide more targeted policy assistance for the domestic supply chain.

In fact, China possesses strong international competitiveness in chip design, packaging, and medium-to-low-end manufacturing, with the exception of advanced 7 nm-and-below manufacturing processes, which are restricted by trade limitations [55]. Furthermore, chips below 7 nm only account for around 1% of automotive applications, indicating China's potential to localize the majority of automotive semiconductor supply chains. The previous chip shortage crisis and the broader context of the China–U.S. strategic competition have also provided Chinese OEMs with the impetus to utilize domestically produced automotive chips. Increasing capital and talent are also flowing into the domestic automotive chip development arena. Moreover, the accelerated localization of other automotive chips may enable China's chip manufacturing capabilities to experience rapid development driven by the large automotive market, ultimately filling the last remaining gap.

5.3. Reconstruction of Technology Stack

The restructuring of the automotive technology architecture will disrupt the traditional relationships between OEMs and semiconductor companies, presenting a wealth of new business opportunities [56]. The conventional automotive technology architecture has relied on Tier 1 component suppliers as intermediaries responsible for sourcing automotive chips and developing integrated software–hardware ECUs. OEMs generally do not engage directly with chip companies, resulting in a lack of mutual understanding and the difficulty of establishing new collaborative relationships. However, intelligent vehicles demand the decoupling of software and hardware, with the computational capacity originally distributed across hundreds of ECUs now being consolidated onto one or a few centralized computing platforms. This transformation has three key implications for the division of labor in the automotive chip industry:

- OEMs will participate in chip design: Future vehicle computing platforms will be highly integrated with the overall software and hardware architecture of the vehicle. To maintain control over the functional performance of the final product, OEMs must autonomously define the application scenarios and specific requirements for the relevant chips and deeply engage in the chip design process [57];
- Chip companies will interact directly with OEMs: As OEMs gradually reclaim the development of computing platforms from Tier 1 suppliers, chips will become a critical component that OEMs need to understand deeply and potentially procure independently. This will necessitate chip companies establishing direct collaborative relationships with OEMs;
- Software developers will be involved in chip development: As mentioned in Section 3.2, only through a high degree of cooperation between software and hardware can the full potential of chip computational be realized. This will lead to software developers participating in the development of the chips.

These new collaborative requirements will compel OEMs, chip companies, and software suppliers to re-evaluate their respective positions in automotive chip cooperation and leverage complementary capabilities to create optimal products.

6. Implications and Suggestions Based on Multi-Case Analysis

In the third phase of our study, we evaluated the effectiveness of the opportunities identified and the development paths proposed in Section 5, based on 3 years of industrial progress. We also summarized practical insights and provided recommendations for further cross-industry collaboration.

6.1. Government-Led Development of Double Smart Cities

"Double Smart Cities" refers to cities that achieve the coordinated development of smart city infrastructure and smart vehicles [58]. In May 2021, China's Ministry of Housing and Urban–Rural Development and the Ministry of Industry and Information Technology jointly designated six cities, including Beijing and Shanghai, as the first batch of pilot cities for double smart city development. In December of the same year, ten more cities were identified as the second batch of double smart city pilots.

In terms of urban digital infrastructure, the 16 pilot cities have installed sensing and interaction facilities, such as visual radars, at over 2000 key intersections and deployed 240,000 5G base stations. This has significantly expanded the market space and application scenarios for the semiconductor industry. A considerable number of new companies related to vehicle-to-everything, roadside sensors, cloud computing, and edge computing have emerged within the industry.

In terms of testing and operating autonomous vehicles, the 16 pilot cities have deployed more than 2000 L4 autonomous vehicles, with a cumulative testing mileage exceeding 30 million kilometers and having served over 4 million people. This extensive testing and operation have not only greatly increased public acceptance of driverless technology but also substantially contributed to the research and development of autonomous driving technologies. Companies such as Huawei and Baidu have seen their intelligent driving solutions advance, achieving urban navigation on autopilot (NOA) from Level 2 Advanced Driver Assistance Systems (ADAS) without an increase in computational capacity.

Therefore, after 3 years of development, the intelligent vehicle infrastructure cooperative system has indeed created significant synergies between the semiconductor and automotive industries. However, it is important to recognize that the current intelligent vehicle infrastructure cooperative system remains at the stage of coordinated perception, with a considerable distance from coordinated computing and decision-making. We recommend that the government further leverage its role in coordinating resources to advance the development of double smart cities. At a macro level, the roadmap for intelligent connected vehicle technology should be further refined to the chip level, clearly defining the functional and performance requirements of chips for different stages of vehicle–road collaboration. This will guide relevant companies in the broader automotive ecosystem—including vehicle computing chips, roadside equipment, and cloud servers—in their collaborative research, development, and application efforts. This approach will accelerate the seamless integration and expansion of both in-vehicle and out-of-vehicle computational capacity.

We also need to be aware of the difficulty for the government to coordinate various resources. The various components of the "Double Smart Cities" operate within different business models and technological environments. Manufacturers of vehicle computing chips may be more focused on global semiconductor market trends while providers of roadside equipment may be more concerned about local infrastructure deployment and compatibility. Coordinating these diverse interests and technological directions is a complex task. The government can play a key role in facilitating the establishment of industry standards for interfaces and communication protocols. This can be achieved through industry forums and standard-setting committees.

6.2. OEM-Led Construction of Local Automotive Semiconductor Supply Chain

With policy support and capital influx, the localization rate of automotive semiconductors has increased significantly, from 5% in 2021 to 10% in 2023 [59]. This is a remarkable achievement for the semiconductor industry, which typically experiences slow capacity growth. As shown in Figure 2, the localization rate of automotive semiconductors exhibits a high–low–high pattern. For low-end chips with manufacturing processes greater than 90 nm, domestic alternatives are becoming increasingly mature, and the localization rate rises rapidly when OEMs' procurement willingness increases. For high-end chips with manufacturing processes less than 28 nm, although foreign products still have performance advantages, these advantages are not substantial. Conversely, domestic companies offer better service capabilities, leading many OEMs to adopt domestic solutions. For mid-range chips, the reliability requirements are extremely high, and domestic solutions lack large-scale in-vehicle application validation. Consequently, OEMs are currently hesitant to adopt these solutions on a large scale. Notably, some OEMs are promoting automotive-grade validation for domestic chips. In September 2021, SAIC-GM-Wuling announced the creation of an open and shared platform for testing, validating, and applying domestic chips [60]. This initiative aims to conduct quality validation in collaboration with chip manufacturers and component suppliers, overcoming technical bottlenecks in compatibility and stability and enhancing the generality, cost-effectiveness, and reliability of domestic chips.

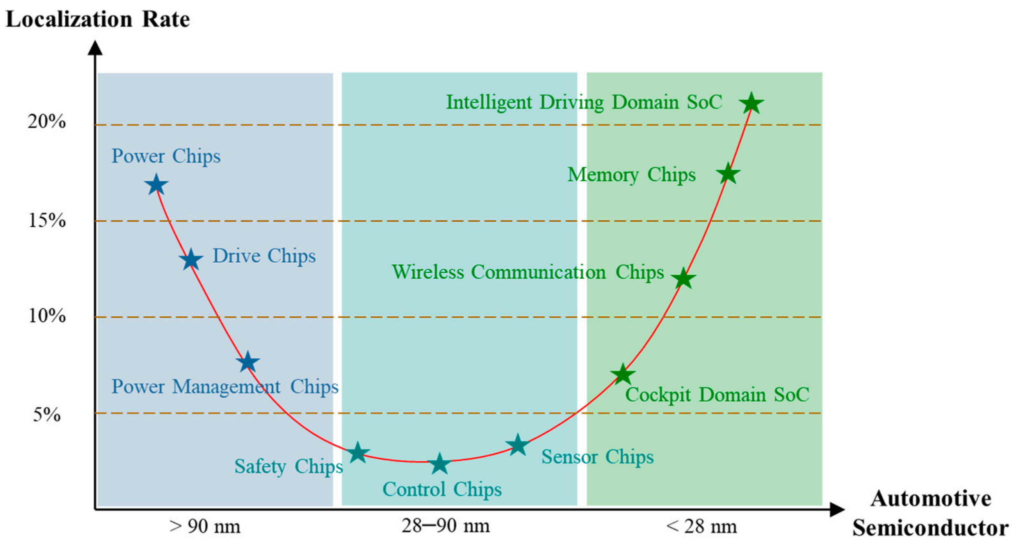

Figure 2. Localization rate of automotive semiconductors in China.

It is evident that the localization of the automotive semiconductor supply chain is an established industry trend, with mutual promotion between China's automotive and semiconductor industries. To further accelerate the increase in localization rate, the core factor is a strong procurement willingness from OEMs. Therefore, we recommend that OEMs, guided by the goal of ensuring stable supply, proactively collaborate with automotive chip manufacturers and related supporting enterprises to strategically plan the supply chain. For low-end chips, OEMs should prioritize domestic solutions and swiftly advance the localization of production and supply. For mid-range chips, OEMs should selectively incorporate domestic products into certain models to aid in the iteration of domestic technologies. They should also promptly facilitate the transfer of localized production capacity and establish a more transparent and agile supply–demand interface mechanism with chip manufacturers. For high-end chips, OEMs should explore new forms of deep collaboration with leading domestic chip companies, such as capital intervention, joint development, resource sharing, and risk sharing. Additionally, they should focus on potential manufacturing resources within China.

The key to the above suggestions lies in breaking the information asymmetry between OEMs and local chip manufacturers. Chip manufacturers may have a better understanding of their production capabilities, technical limitations, and future product plans, while OEMs may be more aware of end-user needs and market trends. This information asymmetry can lead to expectation biases, the over-production or under-production of chips, and inefficiencies in the supply chain. The use of digital platforms and the introduction of generative AI may increase the transparency of the supply–demand interface [61,62]. These platforms can provide real-time information on chip inventory, production plans, and OEM demand forecasts, thus promoting the sharing of interests and risks between the two parties.

6.3. Industry Collaboration to Build a Chip Application Ecosystem

After 3 years of exploration, OEMs and chip companies in China have discovered various ways to collaborate around in-vehicle computing platforms. As shown in Figure 3, based on different OEMs' capabilities in hardware development and hardware–software integration, chip companies can flexibly offer products in various forms, such as IP licensing, SoCs, computing platforms, and complete ADAS solutions [63]. Thanks to these flexible business models, on one hand, numerous chip startups like Horizon Robotics, Black Sesame Technologies, and T-Head have seen substantial business growth, ensuring that China's chip technology in intelligent driving and smart cabins keeps pace with international giants. On the other hand, car manufacturers like NIO, XPeng, and Geely have been able to deeply engage in chip design and even develop their own chips, achieving the synergy of self-developed software algorithms and hardware to create competitive intelligent vehicle products.

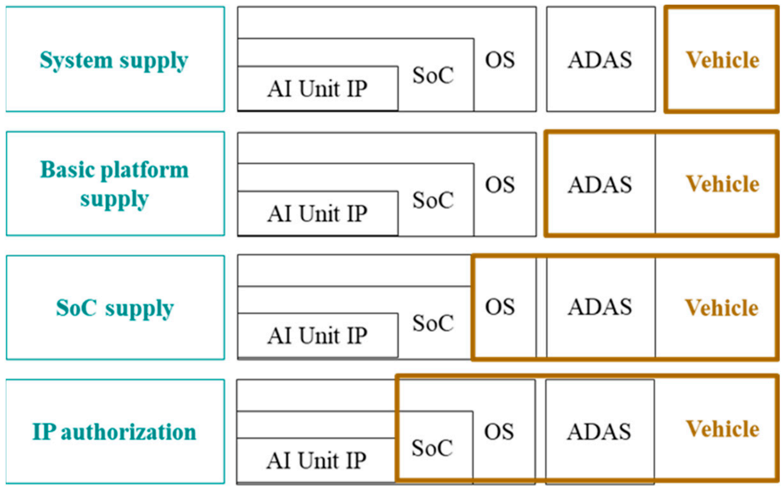

Figure 3. Different cooperation modes between OEM and chip companies.

Although there has been more communication and cooperation between OEMs and chip companies, overall, chip companies often have greater influence due to their specialized design and development capabilities [64]. This often forces OEMs to adapt their vehicle architectures to the capabilities of core chips, deviating from the ideal product development flow and resulting in chip functionalities and vehicle requirements not being perfectly aligned.

To further achieve synergy between chips, vehicle architecture, and software at the product level, the industry should adopt a new ecological cooperation model centered around OEMs, together with chip designers, basic software suppliers, and algorithm suppliers, focusing on the integrated design of hardware and software for automotive main control chips and computing platforms. As shown in Figure 4, there are four suggestions:

- OEMs, as the definers of architecture and integrators of hardware and software, should independently define the requirements for core chips, core algorithms, and operating systems from the perspective of overall vehicle functionality and performance. They should coordinate the development tasks of various hardware and software suppliers to develop the most cost-effective computing platforms;
- Chip designers must effectively connect with the upstream and downstream of the semiconductor industry chain, ensuring that chip design solutions match production capabilities and meet quality requirements;

- Algorithm suppliers and chip designers need to collaborate closely to enhance the efficiency of algorithm utilization of computational capacity. Basic software suppliers should ensure compatibility and adaptation with the chip ecosystem;
- Algorithm suppliers and basic software suppliers should engage in joint optimization based on clear chip solutions to further improve system performance and quality;
- In this ecological cooperation model, conflicts may arise in areas such as corporate culture and technology patents. Joint training and knowledge-sharing initiatives can help bridge the cultural and knowledge gaps among different stakeholders. OEMs can arrange training courses for chip designers, basic software suppliers, and algorithm suppliers, enabling them to understand the unique requirements of the automotive industry, such as safety and reliability standards. In return, other partners can share their technical know-how with the OEMs. This can promote mutual understanding and cooperation, facilitating the alignment of different enterprises towards a common objective.

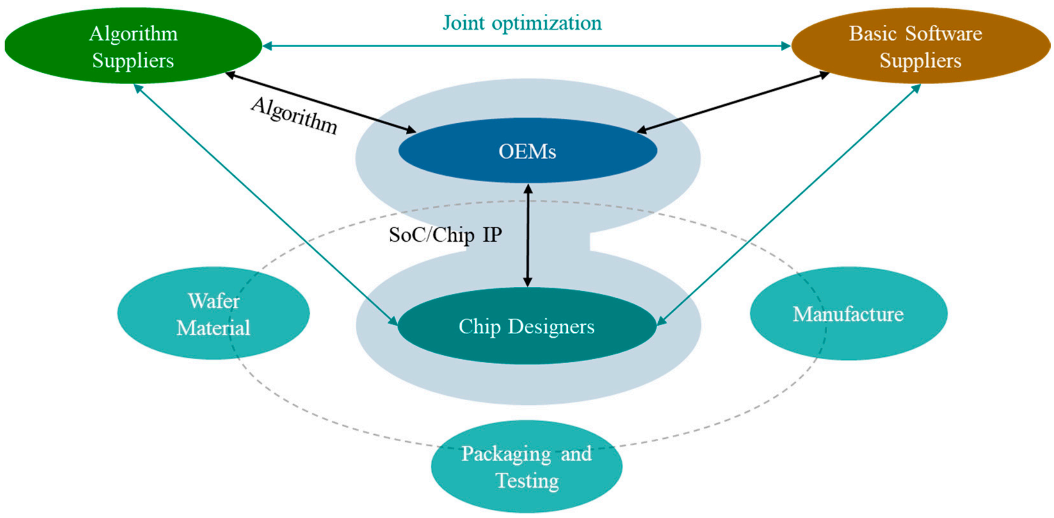

Figure 4. Ecological cooperation model of automotive main control chips and computing platforms.

7. Conclusions

This study, through a three-phase investigation, closely followed the synergistic development process of China's automotive and semiconductor industries. It further emphasizes the necessity of practicing a synergistic development strategy between these two sectors and provides case support and forward-looking recommendations for future development. Table 2 shows three synergistic development paths of the automotive industry and semiconductor industry and their evaluation criteria.

In the first phase, we identified the synergistic development value and challenges between China's automotive and semiconductor industries. The semiconductor industry has the potential to assist the automotive industry in its digital and intelligent transformation from both technological and product perspectives. Conversely, the automotive industry could drive the growth and competitive edge of the semiconductor industry through market and application demands. However, this synergy faces challenges on three fronts: technology, supply chain, and industrial cooperation. From a technical standpoint, the mass production of ultra-high computational capacity in-vehicle platforms poses significant difficulties. In terms of the supply chain, ensuring security and resilience amidst the trends of deglobalization has become a critical concern for OEMs. Regarding industrial cooperation, OEMs must continually refine their boundaries of cooperation with chip companies and related enterprises to develop cost-effective products.

Table 2. Challenges, opportunities, suggestions, and evaluation criteria for the synergistic development of automotive industry and semiconductor industry.

Challenges	Opportunities	Suggestions	Evaluation Criteria
Computational capacity bottleneck of intelligent vehicle	Intelligent vehicle infrastructure cooperative system	Government-led development of double smart cities	Cost of unit computational capacity
Structural risk of automotive chip supply chain	"Chip shortage" crisis	OEM-led construction of local automotive semiconductor supply chain	Market share of domestic automotive chips
Unclear industrial cooperation models	Reconstruction of the automotive technology stack	Industry collaboration to build a chip application ecosystem	Product R&D efficiency

In the second phase, we gathered and distilled insights from industry experts regarding the opportunities and trends in the synergistic development of the two industries, proposing potential development paths to address the three major challenges identified in the first phase. From a technical perspective, the development of an intelligent vehicle infrastructure cooperative system is expected to open new avenues for overcoming the computational capacity bottleneck of intelligent vehicles. On the supply chain front, the "chip shortage" crisis is anticipated to accelerate the localization of China's automotive semiconductor industry. In terms of industrial cooperation, the reconstruction of the automotive technology stack is likely to foster new divisions of labor and cooperative relationships.

In the third phase, we conducted a multi-case analysis spanning nearly 3 years to test the development paths proposed in the second phase. We summarized relevant practical experiences to provide strategic recommendations for better synergistic development in the future. For the intelligent vehicle infrastructure cooperative system, we recommend that the government strengthen top-level design and formulate an integrated chip roadmap for vehicle–road–cloud coordination. Regarding supply chain localization, we suggest that OEMs actively assume the role of supply chain leaders, using demand to drive the construction of a localized automotive semiconductor supply chain. For the industrial division of labor, all industry participants should adopt an open and shared mindset, establishing an ecosystem of cooperation around the integration of automotive software and hardware and exploring new business models.

As the new wave of industrial transformation enters deeper waters, the cross-industry synergistic effects between the automotive and semiconductor industries continue to play a significant role. In particular, the application of generative AI in various industries may further strengthen this synergy [65]. Future research may consider modeling these synergistic effects quantitatively and revealing their underlying mechanisms.

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Abbreviations

The following abbreviations are used in this manuscript:

OEM	Original Equipment Manufacturer
HW	Hardware
SW	Software
SoC	System on Chip
CPU	Central Processing Unit
GPU	Graphic Processing Unit
NPU	Neural Network Processing Unit
R&D	Research and Development
ECU	Electronic Control Unit
ADAS	Advanced Driver Assistance System
OS	Operating System

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