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Impact, Challenges and Prospect of Software-Defined Vehicles

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Abstract
Software-defined vehicles have been attracting increasing attentions owing to their impacts on the ecosystem of the automotive industry in terms of technologies, products, services and enterprise coopetition. Starting from the technology improvements of software-defined vehicles, this study systematically combs the impact of software-defined vehicles on the value ecology of automotive products and the automotive industrial pattern. Then, based on the current situation and demand of industrial development, the main challenges hindering the realization of software-defined vehicles are identified, including that traditional research and development models cannot adapt to the iterative demand of new automotive products; the transformation of enterprise capability faces multiple challenges; and many contradictions exist in the industrial division of labor. Finally, suggestions are put forward to address these challenges and provide decision-making recommendations for enterprises on strategy management.

Keywords Software-defined vehicle · Industrial reconstruction · Automotive industry · Strategic suggestions

Abbreviations

ECU	Electronic control unit
EEA	Electrical/electronic architecture
ICT	Information and communication technology
OS	Operating system
OTA	Over-the-air
R&D	Research and development
SDV	Software-defined vehicle
SOA	Service-oriented architecture
SoC	System on chip
SOP	Start of production

1 Introduction

A new round of automotive industry reform is taking place with the revolution of energy, connectivity and intelligence as the core driving force. The connectivity revolution enables data to fully interact and the intelligence revolution effectively promotes the utilization of data, which complement each other resulting in new automotive technologies, infrastructure as well as research and development (R&D) models, manufacturing and service and finally reshaping the industrial ecosystem [1]. It can be predicted that intelligent vehicles will become the core of digital life in the future, connecting smart transportation, smart city and smart energy and enabling the data to flow [2]. Viewed this way, future vehicles will be defined by data in the era of the Internet of Everything.

Software, as the tool of data generation, circulation and application, will be deeply involved in the stages of R&D, production, sale, operation and service in the whole life cycle of vehicles. The value of automotive software will become increasingly prominent [3]. According to McKinsey's research, the software codes on each vehicle have exceeded 200 million lines, and the market scale of automotive software and related services has exceeded 24 billion US dollars, which will continue to increase at a high speed in the next 5–10 years [4]. For traditional vehicles, hardware is both the necessary and sufficient condition, while software is only auxiliary, while for future vehicles, hardware is only the basic necessary condition, and software is the sufficient condition to determine user experience. Compared with data-defined vehicles, software-defined vehicles (SDVs) can better reflect the change of the relationship between hardware and software and the evolution direction of automotive products. It is the vehicle whose architecture design is

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determined by software, and whose function, performance, service and experience mainly depend on software. It should be clarified that the concept of SDV is not the same as intelligent vehicles. SDV is a measure to create intelligent vehicles, and intelligent vehicles are one of the external manifestations of SDV.

As an unprecedented concept, SDV requires relevant enterprises to actively explore the “no-man’s-land”. On the whole, the industry is still in the state with a clear direction and unclear path. Different enterprises have different understandings of the connotation of SDV, so different development strategies are formulated. Therefore, it is urgent for the automotive industry to systematically and comprehensively comb and analyze the impacts and challenges of SDV and put forward specific and targeted suggestions. This study follows this train of thought.

2 Industrial Reconstruction Caused by SDV

2.1 Changes in Automotive Technologies Promoted by SDV

One of the key technical characteristic of SDV is the decoupling of software and hardware. Software in the component subsystems of traditional vehicles is embedded in hardware. The result of the high binding of software and hardware is the solidification of vehicles' functions and performance. To improve the flexibility of automotive software for better user experience, the component subsystems of traditional vehicles will be gradually layered, and the coupling between technical elements at different levels will be reduced [5].

As shown in Fig. 1, in the decoupling process, the connotation of the original technical elements will change, and new elements will emerge. The technical elements of SDV are summarized as functional hardware, electrical/electronic architecture (EEA), computing platform, operating system (OS) kernel, middleware, service layer of service-oriented architecture (SOA), functional application, service application and cloud service platform. Among these elements, onboard hardware includes functional hardware, EEA and computing platform, which is the competency source of data generation, processing and interaction [6]. Functional hardware includes sensors and actuators, which are responsible for generating data and receiving instructions for corresponding functions. EEA connects all functional hardware and computing platforms through the in-vehicle network to promote data interaction and gathers data on computing platforms for processing [7]. The computing ability of platform determines the ability of data processing inside the vehicle.

Onboard basic software consists of OS kernel, middleware and the service layer of SOA, which can promote the aggregation and cross-use of data among different subsystems and domains [8]. Typical automotive OS kernels include Linux, QNX and other real-time operating system, each of which is responsible for the management of software and hardware of one or more subsystems [9, 10]. Middleware is a technology for communication between distributed systems, which can shield the underlying differences and provide a unified data aggregation platform upward [11]. SOA is a software architecture that takes services as basic components and forms application software through arrangement and combination of services [12]. The service layer of SOA encapsulates the stable and repeated automobile functions as services, thus greatly improving the flexibility and reusability of the upper application software [13].

Above the basic software is the application software for specific business scenarios. Application software can be divided into functional applications and service applications. Functional applications usually involve hardware control and security [14, 15], and service applications are more related to content service and infotainment, such as charging, vehicle anomaly detection and energy service [16–19].

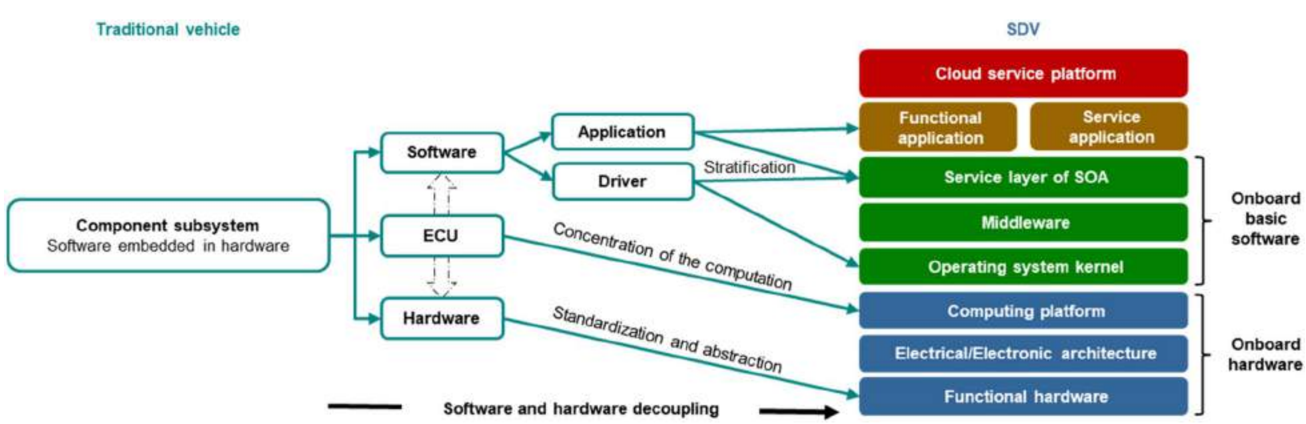

Fig. 1 Map of technical elements of SDV

In the Internet-of-Things era, most of the data generated by software and hardware of vehicles will be transmitted to the cloud [20]. Cloud service platform can process and analyze the data by forming the data closed-loop, thus tapping the potential of data to optimize the user experience through over-the-air (OTA) software upgrade [21]. The data closed-loop has been widely used in vehicle simulation, machine learning, remote repair, cloud control and other fields [22–26].

The development of SDV technology architecture can be divided into three stages, starting from the "hardware-defined stage" to the "software-controlled stage", and eventually reaching the "software-defined stage". At different stages, the software architecture, hardware architecture and functional features of vehicles have different changes. As shown in Fig. 2, three technological development trends of SDV have been illustrated. The analysis is carried out below.

2.1.1 Whitening of the Functional Black Box

Because of the binding of hardware and software, components in traditional vehicles are black boxes for automotive enterprises. To support the continuous iteration of software in the future, functional hardware needs to standardize the interface and abstract the function, so as to be replaceable and upgradable [27]. Based on this, automotive enterprises can decouple software and hardware so that data will be no longer enclosed in subsystems [28]. The original functional black boxes will be white boxes for automotive enterprises. This change will continue to happen with the development of SDV. The control models of most hardware will gradually be mastered by automotive enterprises instead of suppliers.

2.1.2 Concentration of the Computation

With growing data generated in the car, the demand for computing and communication ability in vehicles is increasing. Therefore, the computing unit evolves from electronic control unit (ECU) to domain control unit to central computing platform, and EEA evolves from distributed architecture to domain architecture to central centralized architecture [29]. Eventually, most of the computing ability in SDV will be concentrated on a computing platform, which will be beneficial to OTA software upgrade, improving the utilization of computing resources and reducing hardware redundancy [30].

To achieve the concentration of computation, system on chip (SoC) will be used as the core of computing platform to meet the needs of different computing tasks [31]. Different specialized chips will be integrated into the computing platform [32]. In addition, data interaction with large bandwidth and low latency becomes one of the necessary conditions, for which Ethernet will be used as the backbone of the in-vehicle network to form a new cyber-physical system [33].

2.1.3 Thickening of the Software Middle Layer

To ensure the flexibility and iteration of application software, automotive technology architecture needs a more powerful middle layer. The basic functions required for applications need to be transferred to the service layer of SOA and middleware [34]. The platformization of basic software supports more data interaction across subsystems and

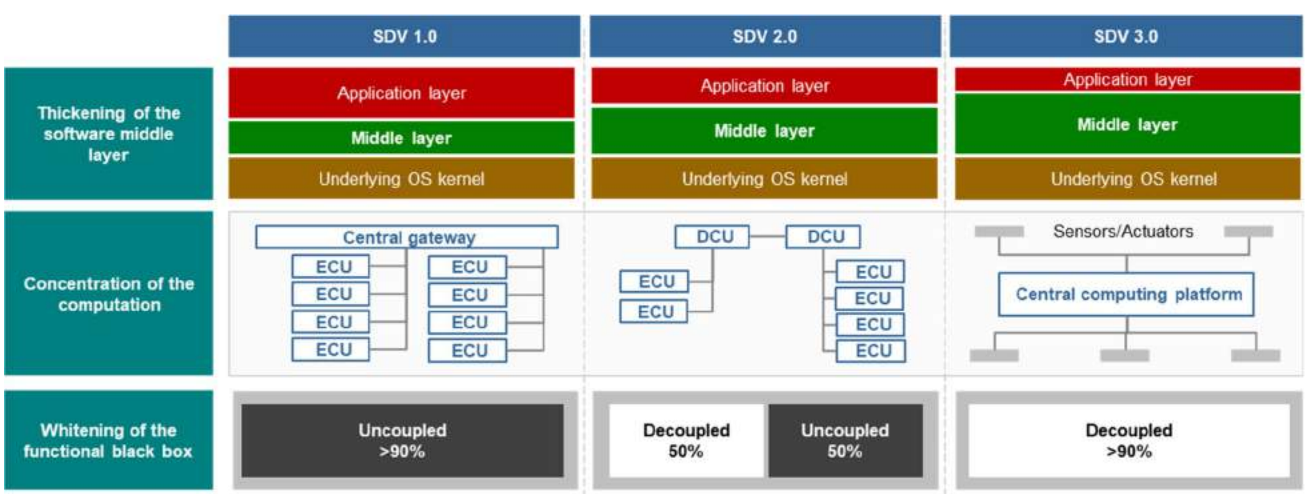

Fig. 2 Technical development trends of SDV

provides an extendible application development framework upwards [35].

Now many enterprises and researchers have invested in the R&D of service-oriented automotive middleware. Communication infrastructure based on IP or data distribution protocol has been widely implemented [36, 37]. The main solutions are changing from the classic platform of AUTOSAR to the adaptive platform of AUTOSAR [38]. The industry has also made a preliminary exploration on the application of SOA in vehicles. Advanced driver assistance systems and human–computer interaction systems based on SOA have begun to appear in the market [39, 40]. In the future, the car-side SOA will be able to cooperate with the cloud-side SOA platform to provide more application services [41].

2.2 Reshaping of the Value Ecology of Automotive Products by Technological Changes

The key significance of the technological changes of SDV is to promote the circulation of data in automotive industry and fully release the potential value of data, thus reshaping the value ecology of automotive products [42]. As shown in Fig. 3, the value increment of traditional vehicles depends on the superposition of hardware, while the embedded software only assists the hardware to complete its functional task. But for SDV, hardware becomes the shared resource that can be called by software, and the flexible combination of hardware and software can achieve more functions and stronger performance. Based on data closed-loop, onboard software can even achieve self-learning and self-evolution in the stage of service.

Specifically, the automotive product value ecology will undergo two major changes. On the one hand, the intelligent and personalized user experience will be greatly improved, such as the high-level and comfortable autonomous driving [43–47]. On the other hand, costs of original automotive products can be reduced. For example, SOA can effectively reduce the complexity and cost of R&D [48], the flexible combination of software and hardware can reduce the redundancy cost [49], and OTA software upgrades can also be used to remotely repair bugs to reduce the recall cost [50].

As shown in Fig. 4, SDV will derive a new value chain along the data flow, whose core logic is to continuously utilize data to optimize the intelligent and personalized user experience of vehicle and meet the needs of consumers. In the process of data generation, with the centralization of EEA and computation as well as the increase of sensors and digital devices, the computing and communication capabilities of the vehicle will be greatly improved so that the quantities and types of data generated will be increased. In the process of data collection, layered decoupled software and service-oriented application development will greatly improve the flexibility of automotive software architecture. The improved software architecture enables automotive software to support data integration across components, systems and domains, for which the potential value of data will be increased. In the process of data processing, storage, analysis and utilization, cloud service platform will undertake all data-related tasks. A typical case is Tesla's shadow model of autonomous driving in the cloud, which uses the real-time data of vehicles to train the algorithm [51]. With the improvement of cloud platform capabilities, the utilization rate of data by related enterprises will be increased and the data potential will be fully released. In addition, innovation will also take place in

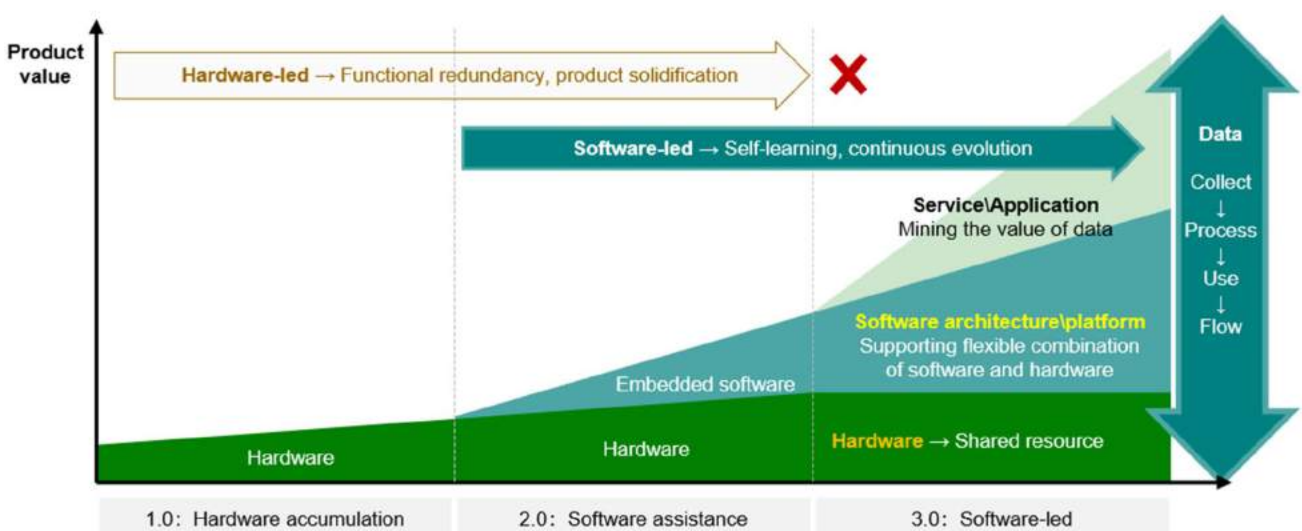

Fig. 3 Changes in the value ecology of automotive products

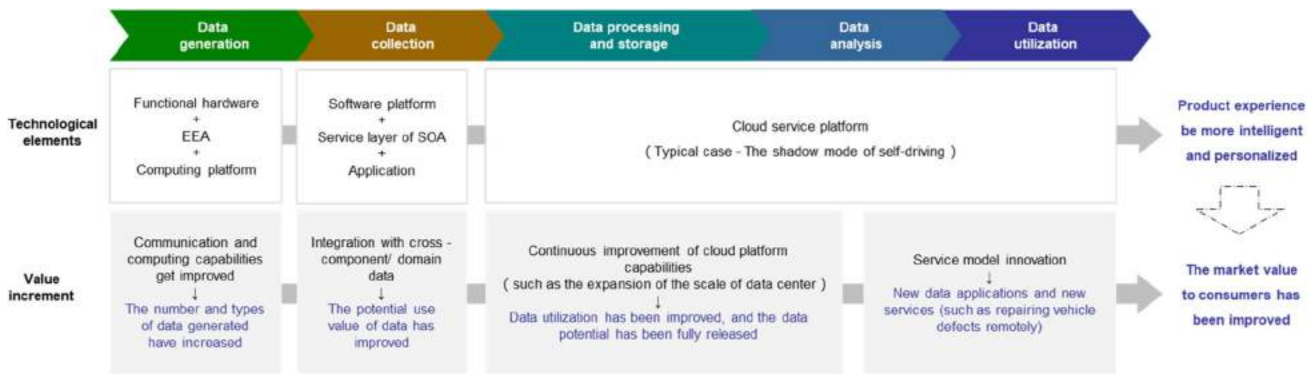

Fig. 4 Data value chain of SDV

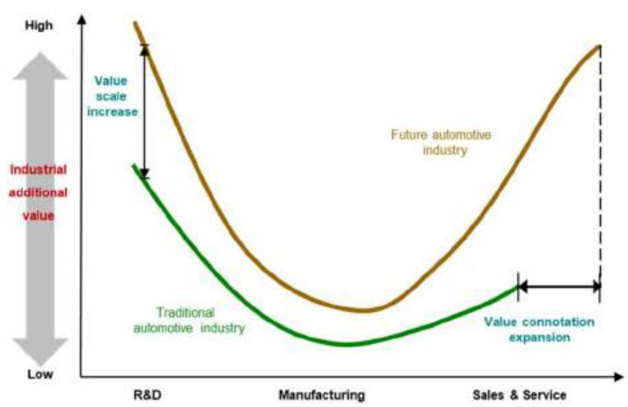

Fig. 5 Comparison of smile curves between traditional and future automotive industry [52]

the services of automotive industry. The data will be applied to emerging services, such as remote repair of vehicle defects by OTA software upgrade. Through the data closed-loop, the market value of vehicles will be improved.

2.3 Reconstruction of the Industrial Pattern Through New Value Ecology

Figure 5 shows the change of the additional value of each stage in the automotive industrial chain with the development of SDV in the form of smile curve. Since software is the main measure to achieve value increment brought by SDV, the additional value increment of the industrial stages will increase with deeper software participation. In the stage of R&D, hardware architecture is defined by software architecture. With the increase in the quantity and complexity of software, software will contribute the major value. In the manufacturing stage, although hardware can be expanded after standardization and abstraction, the value increment is limited. In the sale and service stage, the proportion of software in Bill of Materials will be constantly increasing, and software can also make profits constantly through OTA upgrade or subscription services. In addition, relevant enterprises can provide diversified services for users by software; thus, not only the value increment in this stage is the most, but also the value connotation can be expanded by broadening the automotive industrial boundary.

Confronting the additional value brought by SDV, all kinds of enterprises are willing to seize the opportunities and gain benefits [53]. Traditional players in the industrial ecosystem, such as automotive and component enterprises, will actively transform, and new players will also enter the game at the same time. The automotive industry which was fragmented and had high barriers will be reconstructed. As shown in Fig. 6, the evolution of automotive industrial pattern can be divided into three stages according to resources from an industrial the authors are working for.

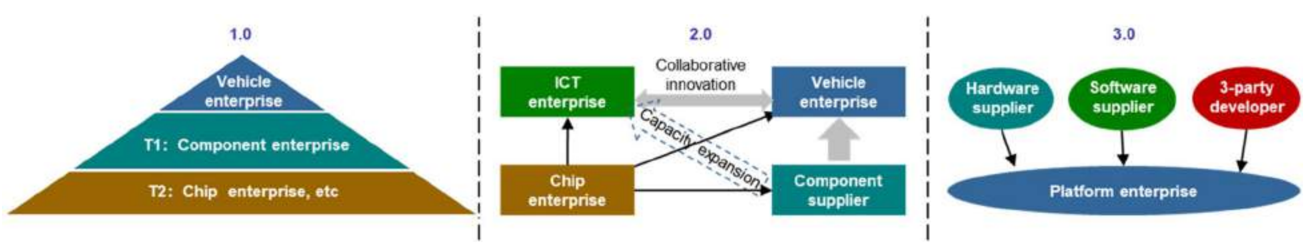

Fig. 6 Three stages of the evolution of automotive industrial pattern

The industrial pattern in Stage 1.0 was in a chain-type structure. Automotive enterprises coordinated the whole industrial chain and have an absolute control. In addition, the stages of the industrial chain were relatively independent and closed. For example, chip enterprises were only responsible for supplying chips and would not consider collaboration with upper-level algorithms, and component enterprises would not consider combining with products from other suppliers. At this stage, the automotive products were limited in functions and performance and highly homogeneous in user experience, which made it difficult to meet the personalized needs of users.

The industrial pattern in Stage 2.0 is in a net-type structure. There are three major changes compared with stage 1.0:

(1) Since software gradually becomes the core competitiveness of automotive products, information and communication technology (ICT) enterprises with strong capabilities in software R&D will enter the automotive industry as Tier0.5 to create collaborative innovation with automotive enterprises;
(2) Giant component enterprises and automotive enterprises will gradually expand their capabilities to the ICT field, and the business boundaries between industrial participants will gradually blur;
(3) With the increasing requirements of vehicles for the integration of computing units, the importance of chips has been enhanced. Chip enterprises will have the opportunity to directly supply to automotive enterprises as Tier1.

The industrial pattern in Stage 3.0 will be the structure as a platform and an ecosystem. The platform enterprise, as the integrator of all elements, will be at the center of industrial pattern and master the right to define the vehicle architecture and integrate software and hardware. Hardware suppliers and software suppliers will develop various software and hardware products based on the platform and user needs, and the importance of software suppliers will be further increased with the increment of software value. Moreover, the entry of third-party developers will connect the automotive industry to a wider external application ecosystem, such as smart cities, and the industrial boundaries will also gradually blur.

3 Challenges on the Realization of SDV

To promote the development and implementation of SDV, it is necessary to identify the key problems faced by automotive industry at present. Clarifying the industrial status quo is the basis of analyzing the challenges. Table 1 shows the capability status of technical elements of SDV and the typical industrial division of labor, which are summarized from extensive literature investigation and case analysis [54–63].

It can be known from Table 1 that due to the limitation of technological level and the game between automotive enterprises and suppliers, the development progress of various technical elements of SDV is different, and there are obvious weak spots in the middleware and service layer of SOA. Moreover, the industrial division of labor has not yet got rid of the shackle of the supply relationship of the traditional automotive industrial chain. These reasons result in that the current automotive products are far from the ideal state of SDV, and the potential value of data has not been fully released. Many factors are hindering the realization of SDV, among which the outdated R&D model, backward enterprise capability and unreasonable resource combination are three major challenges.

3.1 The Traditional R&D Model Cannot Meet the Needs of Vehicle Iteration

As shown in Fig. 7, the R&D model of traditional vehicles follows the V-process, whose requirements are decomposed layer by layer and interrelated, and each link has strict restrictions and inflexible delivery deadline, which make it difficult to achieve rapid development and change of software. In addition, for traditional vehicles, software can only be tested after being embedded in hardware, which prolongs the iteration cycle of software, and postpones the responds of user needs [64].

To achieve agile iteration of automotive products, the R&D of software and hardware should be separated and independently verified so that software and hardware can evolve in different cycles [65]. Moreover, software R&D also needs to achieve self-learning and self-evolution driven by data with the help of a highly automated toolchain. At the same time, it should be noted that vehicle R&D has the necessary safety baseline and unique logic; thus, it is infeasible to directly copy the R&D model in the ICT field, such as agile development [66]. It is necessary to effectively integrate the traditional vehicle R&D model with the R&D model in the ICT field.

3.2 Multiple Challenges to the Transformation of Enterprise Capability

Most of the capabilities of traditional automotive enterprises focus on the R&D and manufacturing of hardware. However, the construction of internal software capability is a complex systematic project, which needs to be changed from top to bottom, facing challenges of talent team, organizational structure and enterprise culture.

Table 1 Development status of SDV technical elements

Technical element	Technical capability status	Typical industrial division of labor
Functional hardware	Giant component enterprises master most traditional functional hardware, such as brake ICT enterprises and chip enterprises master most new functional hardware, such as LiDAR	Suppliers responsible for providing hardware products Automotive enterprises responsible for the integration and application of functional hardware
EEA	Automotive enterprises and some giant component enterprises master the core capability in EEA R&D Most advanced products still in the stage of domain architecture	Automotive enterprises dominate EEA R&D Giant component enterprises participate in the design of EEA and provide components
Computing platform	Chip enterprises master the core capability in the R&D, manufacturing, packaging and testing of chips Some vehicle enterprises and giant component enterprises master the capability in the integration of computing platform	Chip enterprises provide the SoC Automotive enterprises or giant component enterprises responsible for the system integration of software and hardware
OS kernel	A few ICT enterprises master the core technologies Some mature OS kernels can be migrated to vehicles, but lack of customized development for vehicle	ICT enterprises provide the kernel products Automotive enterprises or giant component enterprises responsible for the integration and deployment
Middleware	ICT enterprises master the core capability in middleware R&D Some giant automotive enterprises and component enterprises have been jointly formulating the industrial standards	Automotive enterprises or component enterprises adopt industrial mainstream standards, such as AUTOSAR, and the third-party toolchain for R&D
Service layer of SOA	ICT enterprises have the stronger development capability Automotive enterprises or component enterprises have a deeper understanding of the vehicle's scene and architecture design Only a few vehicle products with cockpit SOA	Automotive enterprises or component enterprises dominate the SOA design ICT enterprises undertake major development tasks
Functional application	Giant component enterprises master the core capability in controlling hardware by software Complex functions are difficult to mass-produce in a short time, such as self-driving	Giant component enterprises provide software bounding with hardware Automotive enterprises are responsible for the integration and deployment of functional applications
Service application	ICT enterprises master the development capability and operation experience Automotive enterprises have not completely opened the application ecology	ICT enterprises responsible for the partial development and operation Automotive enterprises responsible for the supervision and partial development and operation
Cloud service platform	Automotive enterprises master the ownership and management of data Suppliers master the data analysis capability of relevant products An open cloud data ecology has not yet been built	Automotive enterprises responsible for the recycling, distribution and operation management of data Suppliers responsible for analyzing data and developing software

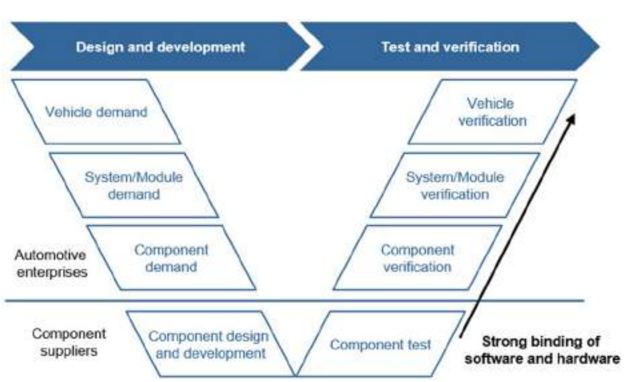

Fig. 7 V-model in traditional vehicle R&D

In terms of talent team, due to the safety requirements of automotive software, the R&D team needs cross-border talents with abilities of both hardware and software design. The two main sources of software talents in automotive enterprises, i.e., the Internet field and the traditional automotive electronics field, are difficult to meet the requirements. Although the talents from the internet field have the skills and experience in developing large-scale software, they are not familiar with the knowledge of automotive hardware. The talents from the traditional automotive electronics field are familiar with the R&D of the underlying hardware but lack the agile development capability of software architecture. In addition, the salary of software talents in automotive enterprises with low-profit margins is not competitive with that in ICT enterprises. As a result, it is extremely difficult for automotive enterprises to recruit software talents.

In terms of organization, the organization structure of traditional automotive enterprises is often not flat enough as it should serve the hardware R&D model. There is little horizontal communication between departments, and most departments follow a one-line reporting process [67]. However, SDV requires all departments of automotive enterprises to respond to market demands in time and carry out agile iteration of software, which means the organizational structure needs to be re-divided based on user-oriented business.

In terms of enterprise culture, the traditional hardware R&D model leads to the rigorous engineer culture in automotive enterprises. In the process of R&D, project teams often want to make everything as controllable as possible [68]. However, there is a fundamental contradiction between this culture and the requirement for software talents to have innovative and agile thinking. If two kinds of talents are blindly mixed to form a team, there will inevitably be many conflicts in thinking.

3.3 Contradictions in the Industrial Division of Labor

Since there are too many technical elements involved in SDV, automotive enterprises cannot do all self-R&D, and the division of labor and cooperation is the inevitable choice. At present, there are contradictions in the division of labor and cooperation between automotive enterprises and suppliers in many fields, and if these problems are not properly resolved, industrial resources cannot be effectively combined.

As for functional hardware, if the interface standards of each automotive enterprise are different after standardization, the component enterprises need to carry out customized R&D, and the cost will be greatly increased. After the abstraction of the control model, the functional hardware and functional applications can be developed independently. As a result, component enterprises may be deprived of the right of software R&D by automotive enterprises and lose market share. Therefore, it is difficult to promote the standardization and abstraction of functional hardware in the cooperation between automotive enterprises and component enterprises.

As for the core software and hardware at the higher level, except for the definition right of EEA and SOA, there are many choices for automotive enterprises in the R&D of computing platform, OS kernel, middleware and applications, such as self-R&D, outsourcing and cooperation. In the division of labor of these elements, a series of problems appeared, such as how to determine the boundary of self-R&D, how to give full play to respective advantages in cooperation and how to effectively cooperate between outsourced products and products by self-R&D.

Besides hardware and software, the data will also cause automotive enterprises to play games with suppliers [69]. After the decoupling of hardware and software, to master the OTA software upgrade independently, automotive enterprises tend to understand the software logic of components and use the data to iterate over software. For the data of vehicles and users belonging to automotive enterprises, when automotive enterprises do not support data backflow, the suppliers cannot iterate over their products based on big data and face the risk of losing market competitiveness. It follows that the game around data is also one of the key problems hindering the realization of SDV.

4 The Industrial Development Suggestions for SDV

4.1 Changing the Vehicle R&D Model to Adapt to SOP-X

SDV requires that user experience can be continuously optimized through OTA software upgrade or online service, which means that automotive enterprises must continuously operate, maintain and develop vehicles based on users' needs to iterate the version of automotive products continuously, namely SOP-X. As shown in Fig. 8, this study develops an innovative R&D model. Considering the safety requirements and integration specifications of vehicle, the new R&D process still needs to follow the framework of the V-model as a whole [70]. But to achieve the agility and flexibility of SOP-X, the R&D of hardware and software must be separated, and automotive enterprises should create an EEA R&D platform, a software R&D platform and an automatic data closed-loop platform based on the characteristics, requirements and iteration cycles of hardware, software and algorithms. The EEA R&D platform should support the expansion and upgrade of hardware based on standardized interface and modular design [71]. The software R&D platform should have a complete toolchain and environment based on SOA to support the agile development of software. The automatic data closed-loop platform should support the real-time optimization of algorithms and the automation of testing through automatic recovery, classification, labeling, training and evaluation of data [72].

Before the first start of production (SOP), the main difference between the new process and the traditional process lies in the separation of R&D and testing of software and hardware. When the function and performance meet the basic requirements, the vehicle can be released as the initial version. In the use stage, the data will be fed back to the cloud service platform in real-time. To achieve SOP-X, part of data will flow to the software R&D platform for the R&D of new functions and to the automatic data closed-loop platform

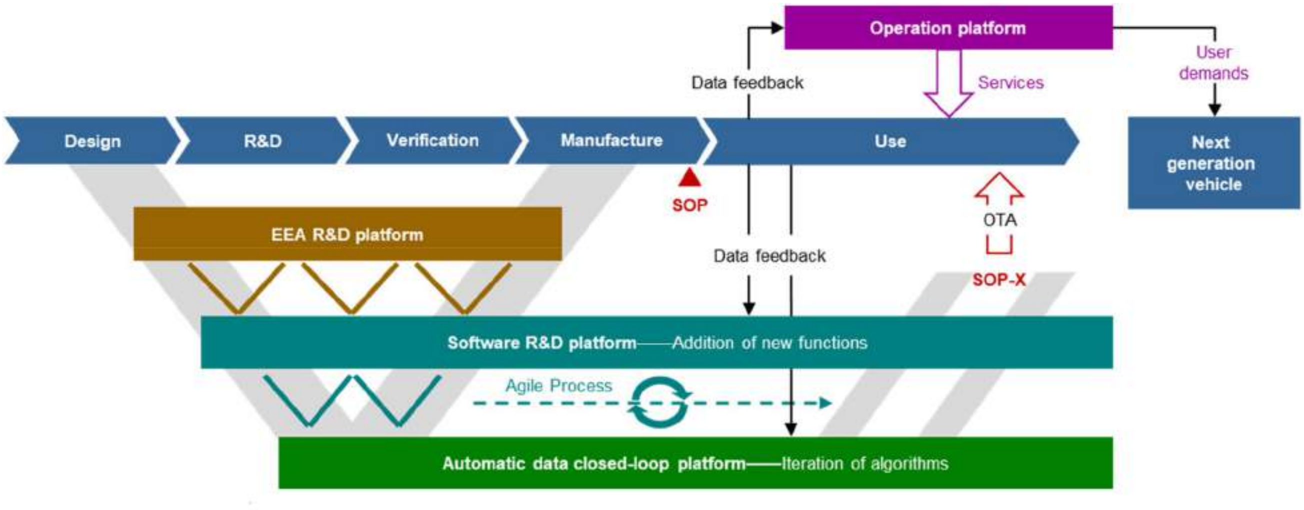

Fig. 8 Innovative R&D model of SDV

for the iteration of algorithms. The other part of data will flow to the operation platform to help enterprises know the user's needs, thus providing personalized mobility services and accumulating experiences for the future R&D.

4.2 Reforming the Internal Organization and Talent of Enterprise

The new R&D model cannot work without the support of organizational structure and talents. As shown in Fig. 9, this study designs a new organizational structure. Agile iteration of software requires enterprises to use data to analyze users' needs quickly, to develop software efficiently and to deliver software to users' vehicles in time and accurately. The three kinds of capabilities depend on the professional data analysis department, centralized R&D system and standardized software management department, respectively.

The data analysis department is mainly responsible for extracting valuable information from massive, scene-based and multi-sourced data [73], which can be used for the analysis of user experience feedback and behavior, the monitoring and diagnosis of vehicles, the training and evaluation of algorithms, and the business analysis based on big data. The main talent demand of this department is data analysts who are proficient in data processing and statistical application.

After a round of processing, the data that can be used for R&D will flow to the R&D center. The R&D center is divided by business applications with a flat structure. The R&D of software and hardware in every team is separated but coordinated with each other, thus ensuring that software and hardware can be effectively integrated to meet the function and performance requirements. To break the barriers between different teams and promote horizontal communication, the R&D centers should be unified at three levels:

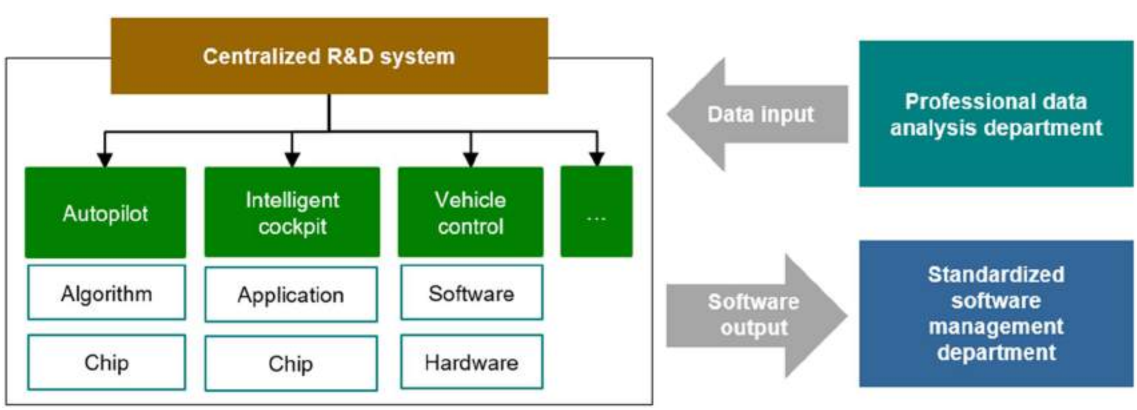

Fig. 9 Organizational structure supporting SDV

- Unified data platform: all the management, scheduling and use of data are completed on this platform.
- Unified hardware architecture: the communication network topology, hardware requirements and interfaces have been defined in advance.
- Unified software architecture: the structure of SOA, functional requirements and interfaces of basic software modules have been defined in advance.

The R&D center firstly needs some architecture engineers who have an outstanding understanding of hardware, software and user needs to optimize the vehicle architecture. Then, in each business team, user experience engineers are required to give optimization suggestions to the features of products from the user's perspective, and software engineers who are proficient in coding are required to upgrade the software package. Finally, integration and test engineers are required to integrate the software and verify the expected function and performance.

After the development of software, the software management department is required to safely and accurately upgrade the software on different vehicles according to different requirements [74]. This department is responsible for managing software information (including software version, update history, market stock and distribution of each vehicle), software packages (including content modification, ownership change, storage, use and deletion of software packages), software source codes (including matching, uploading, storage and calling of source codes) and software defects (including safety monitoring, problem feedback, cause finding, repair and post-optimization). Therefore, its main talent demand is the operation and maintenance engineer with abilities to maintain the high availability of a series of services, and optimize the system architecture steadily to improve deployment efficiency and resource utilization [75].

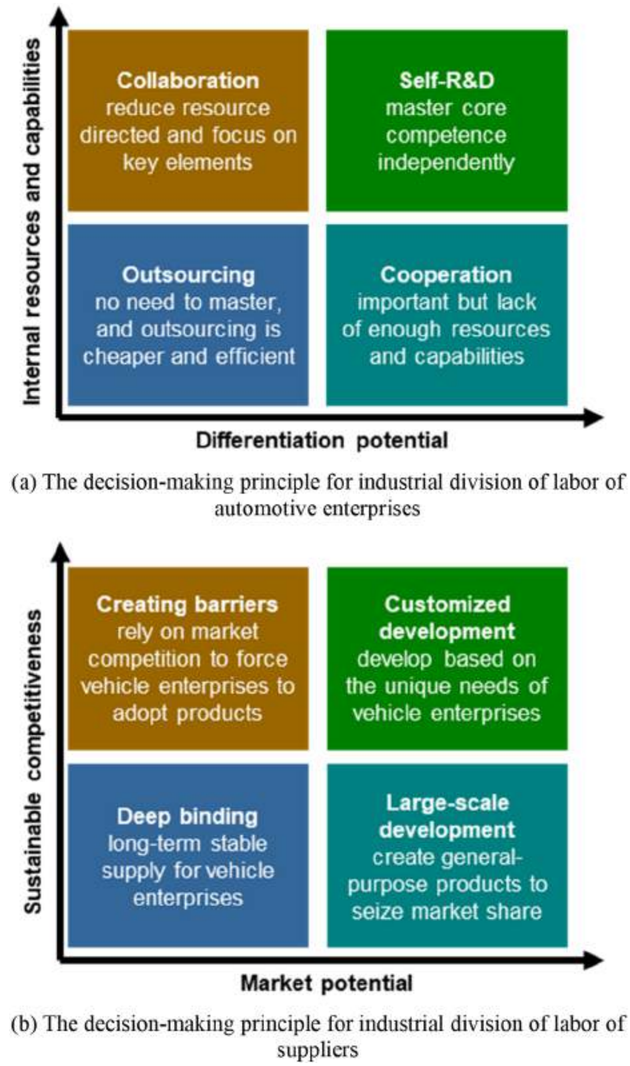

Fig. 10 Decision-making principles for industrial division of labor of automotive enterprises and suppliers

4.3 Combination of Industrial Ecological Resources

SDV cannot be realized by automotive enterprises only, and it is the only way to rationally combine industrial ecological resources, whose premise is that automotive enterprises and suppliers can reasonably divide work. This study extracted the decision-making principles for industrial division of labor of automotive enterprises and suppliers from resources belonging to an industrial the authors are working for (according to Fig. 10). Some feasible suggestions on the industrial division of labor are put forward based on these principles.

Automotive enterprises consider the industrial division of labor from two major dimensions, i.e., the differentiation potential and the internal resources and capabilities. Their decision-making principle can be summarized as follows: pursuing differentiation as much as possible with sufficient internal resources and capabilities. The differentiation potential of a technical element specifically refers to whether automotive enterprises can make differentiated products and create high added value for consumers by investing in this element. The internal resources and capabilities of an enterprise include internal knowledge, talents, R&D tools, organizational structure and management capabilities, which can be used to distinguish between "strong automotive enterprises" and "weak automotive enterprises". There are usually four choices for automotive enterprises: outsourcing, collaboration, cooperation and self-R&D [76].

Suppliers mainly consider the industrial division of labor from two dimensions, which are the market potential and the sustainable competitiveness. Their decision-making principle can be summarized as follows: improving product competitiveness as much as possible under the premise of ensuring the market share. The market potential of a technical element specifically refers to the demand of automotive enterprises for supplier's products. While sustainable competitiveness reflects whether suppliers can keep products differentiated, leading in the market and irreplaceable for a long time to ensure survival in the industrial transformation, which can be used to distinguish between "strong suppliers" and "weak suppliers". There are usually four choices for suppliers: deep binding, creating barriers, large-scale development and customized development.

There will be different choices of the industrial division of labor when different enterprises face the same technical element and the same enterprise faces different technical elements. Here are some specific suggestions for the industrial division of labor around each element.

4.3.1 Industrial Division of Labor Around Functional Hardware

From the perspective of industrial development, the standardization and abstraction of functional hardware is an inevitable trend and the common demand of all automotive enterprises. Therefore, suppliers should not refuse to change, instead, they should actively strive for reasonable benefits in the cooperation with automotive enterprises. Strong suppliers can choose to work with automotive enterprises to formulate interface standards and cooperate in the R&D of corresponding software solutions. Weak suppliers can maintain a long-term supply relationship with automotive enterprises to make up for the extra costs. In the long run, the whole automotive industry can formulate a unified functional interface standard and create an industrial hardware platform, thus promoting the division of labor and cooperation around functional hardware.

4.3.2 Industrial Division of Labor Around Computing Platform

The industrial division of labor around computing platforms can be divided into R&D and manufacturing. In the R&D phase, automotive enterprises and chip enterprises should cooperate deeply to achieve the complementarity of scene understanding and design ability. Strong enterprises should focus on improving abilities of chip design to master more definition rights in the cooperation. In the manufacturing phase, regardless of the manufacturing process or cost control, chip enterprises have absolute advantages over automotive enterprises [77]; thus, automotive enterprises should outsource to suppliers.

4.3.3 Industrial Division of Labor Around OS Kernel and Middleware

Since OS kernel has limited influence on the differentiation of upper-level applications, and ICT enterprises have obvious technological and cost advantages in R&D, strong automotive enterprises should consider outsourcing to suppliers for customized development. While weak automotive enterprises can consider appropriately reducing technological requirements and continue to use existing products.

Middleware plays a key role in the interaction between functions, which has great differentiation potential, but the complexity and cost of R&D are in a high level. Therefore, strong automotive enterprises should give priority to self-R&D of parts without mature solutions, such as self-driving middleware, and other parts can adopt third-party solutions, while weak automotive enterprises should actively seek cooperation with strong suppliers.

4.3.4 Industrial Division of Labor Around EEA and the Service Layer of SOA

EEA and the service layer of SOA determine the integration of hardware and software of the whole vehicle, respectively, which has a great influence on the differentiation of vehicles. Thus, most automotive enterprises cannot give up the definition right of these two elements, and suppliers should actively cooperate, such as providing the automotive enterprises with R&D tools and architecture design ideas.

4.3.5 Industrial Division of Labor Around Applications

For functional applications related to safety and hardware control, strong automotive enterprises should strive for self-R&D as much as possible. For those parts that cannot be self-developed at present, enterprises can temporarily seek help from suppliers and gradually achieve self-substitution in the future. Weak automotive enterprises should maintain a long-term strategic cooperative relationship with the suppliers to ensure the continuous optimization of functions and performance. For service applications, all automotive enterprises should create an open ecosystem and get third-party developers from the field of consumer electronics or Internet involved so that ecological resources can effectively meet the individual needs of users.

4.3.6 Industrial Division of Labor Around Cloud Service Platform

Automotive enterprises should be responsible for the operation, management and supervision of the cloud service platform. Thus, the key problem of the industrial division of labor around cloud service platforms is to avoid the game around the data between automotive enterprises and suppliers. This problem needs to be solved in different scenarios:

For strong automotive enterprises and strong suppliers, both have strong capabilities, and there may be competition between them in the R&D of software. Both sides should try their best to avoid the complete closure of data because the necessary data flow is of positive significance to the industrial ecosystem [78]. The two sides can exchange reasonable interests, for example, the suppliers can pay some authorization fees to the automotive enterprises to get data.

For strong automotive enterprises and weak suppliers, the analysis and utilization of data will inevitably be dominated by automotive enterprises, while automotive enterprises should selectively share some data with cooperative suppliers, thus full taking suppliers' technological advantages in some elements to achieve the cost reduction or experience improvement.

For weak automotive enterprises and strong suppliers, the two sides should maintain a strategic cooperation relationship. Automotive enterprises should share the suppliers related data after desensitization, and suppliers should make customized development plans according to the needs of automotive enterprises so that the products can be continuously improved and automotive enterprises have a relatively strong position in the product definition.

For weak automotive enterprises and weak suppliers, the two sides should not be antagonistic, rather they should achieve data sharing, cooperative analysis and utilization of data, and even team integration.

4.3.7 The Supply Relationships and Business Models Supporting the Industrial Division of Labor

The above-mentioned industrial division of labor cannot be sustained for a long time without a money guarantee, and the traditional business model of one-off sales of vehicles is unable to provide such guarantee for relevant enterprises. Continuous sales of software and services with high profitability have become a new business model of SDV, and brand-new supply relationships are needed. As shown in Fig. 11, for the consumer-oriented business, automotive enterprises can let users choose software at the first sale, and continuously sell new software or subscription services through OTA upgrade after delivery. Even in the future, not only automotive enterprises will face consumers directly, third-party developers can also directly connect with consumers through APP store [79]. For the enterprise-oriented business, suppliers can sell codes, software packages and supporting technical services to automotive enterprises. Besides one-time buyout, suppliers can also charge licensing fees or sales shares.

The new supply relationships and business models will effectively promote the implementation of the industrial division of labor and turn it into real income, thus supporting the rational combination of industrial ecological resources and further pushing forward the change of the automotive industrial ecosystem.

5 Conclusions

This study identifies three major technological trends of SDV, which are the concentration of the computation, whitening of the functional black box and thickening of the software middle layer. As a result, software and hardware are decoupled, and software can freely call and control hardware, thus realizing the continuous evolution of automotive products driven by data and continuously creating new experiences for users. Under this background, the value ecology of automotive products will gradually be dominated by software and attract old players to actively transform and new players to enter the market.

However, because it is difficult to accomplish the improvement of technological level, the change of R&D

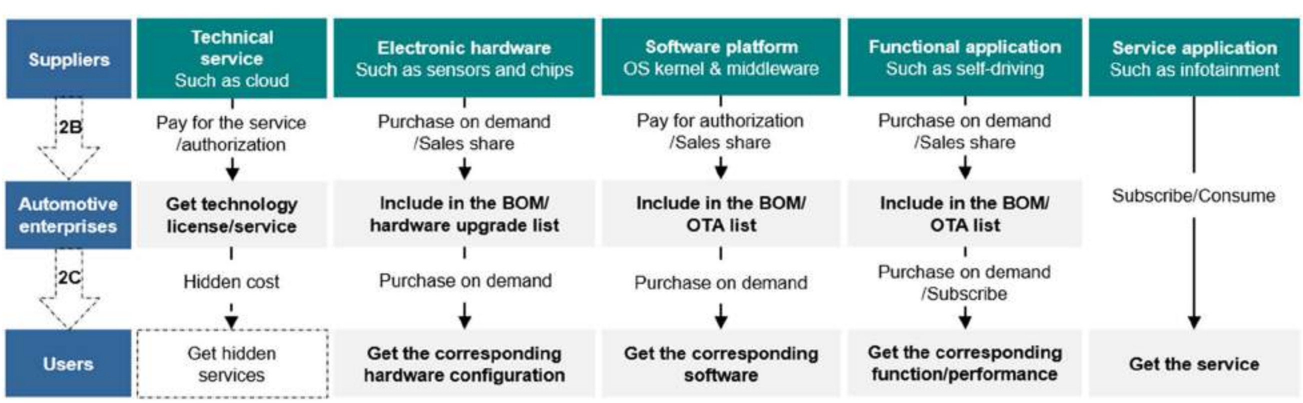

Fig. 11 New supply relationships and business models of SDV

model, the transformation of enterprise capabilities and the industrial division of labor, the effective combination of industrial ecological resources has not yet been achieved. The development process of various technical elements of SDV is different, and the ideal products cannot be effectively created. The following suggestions are put forward for automotive enterprises, suppliers, government and industrial organizations:

(1) As the owner of automotive products and brands, automotive enterprises should take the lead in the development of SDV. It is essential to focus on the creation of different user experiences based on the brand-new organization, team and R&D mechanism. Choosing suitable partners and business models to jointly create an open ecosystem is also important.
(2) On the basis of increasing investment in software, suppliers should make full use of their technological or cost advantages in some elements to meet the needs of automotive enterprises from customization, standardization to other dimensions. Besides, suppliers should also actively participate in the cooperative industrial ecosystem and try to play an indispensable role.
(3) The government or industrial organizations should promote the technical development and industrial cooperation of SDV from the macro or medium level, such as promoting the standard setting of common technical elements like basic software and building the ecological cooperation platform to help enterprises connect.

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Declarations

Conflict of interest On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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