Received November 23, 2020, accepted November 29, 2020, date of publication December 2, 2020, date of current version December 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3042019

Revealing Technology Innovation, Competition and Cooperation of Self-Driving Vehicles From Patent Perspective

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This work was supported in part by the National Natural Science Foundation of China under Grant 71974096.

ABSTRACT Self-driving vehicle (SDV) has become a new driving force in the automotive industry, but no scholars have yet to dig deep into the competitive technology intelligence in the SDV field. Therefore, this study analyzes technology, competition and cooperation from the perspective of global patents, aiming to provide a reference to governments, enterprises and research institutions to grasp the competition situation and timely find the new investment opportunities. In this study, the Derwent Innovation Index (DII) is selected as the data source, the Jaccard index instead of the International Patent Classification (IPC) co-occurrence frequency is used to reflect the technical correlation, Relative Technology Advantage (RTA) index and the International Business Potential (IBP) are used to represent the competition among enterprises, and multiple network indicators, including macro and micro, are used to measure cooperation. The results show that: 1. Vehicle control system is the most critical technology in SDV field; 2. Different types of companies show different competitive advantages. Auto manufacturing companies rely on their strong comprehensive strength to maintain their position, but component suppliers are most likely to become a powerful group to shake the existing industry order. 3. As far as global cooperation is concerned, the partnership led by core leaders is taking shape, but it is still in the early stage.

INDEX TERMS Patent analysis, self-driving vehicle (SDV), social network analysis (SNA), competitive advantage, cooperation relationship.

I. INTRODUCTION

As an important part of the intelligent transportation system, the self-driving vehicle (SDV) has become a disruptive innovation in the automotive industry. SDVs will help manage the road network more rationally and reduce traffic congestion and emissions [1]. Most importantly, many accidents that have caused human error can also be avoided [2].

SDV has received adequate attention from inventors and investors all over the world. Especially in the past five years, despite the many controversies about safety and legal liability during the same period, the research and development in this field has maintained a high degree of activity [3], [4]. General Motors spent $1 billion to acquire Cruise, a startup engaged in SDVs. Toyota built its global R&D network in SDVs through research institutes in Asia, North America and Europe, and set up a venture capital fund to support entrepreneurs and integrate its industry chain. Volkswagen and Ford announced that they will launch the first SDV in 2021 [5], [6]. Not only automobile manufacturers, but also technology giants such as Google have also shown great interest in SDVs. Google launched its plan on SDVs in 2009 and established Waymo in 2016 to specialize in SDVs. Although it is still on the road, the cruise control system (CCS), the automatic parking system (APS) have been widely used in vehicles, which laid a foundation for fully SDVs. Furthermore, according to the road map to autonomous and connected driving in 2030 published by the European Commission, the high-level SDVs will come true in some cities between 2024 and 2030.

But as a disruptive innovation, the emergence of SDV technology has also changed the competitive landscape. Therefore, this sustainable technology urgently needs an in-depth

The associate editor coordinating the review of this manuscript and approving it for publication was Baozhen Yao.

competitive technical intelligence (CTI) to help SDV stakeholders grasp its research topics, hotspots, major competitors and their partners [7], which are invaluable to both the 'old aristocrats' and the 'new forces' in the SDV field, as well as wait-and-see people outside the field. However, most of the current researches focuses on the improvement of the technology involved in SDV, and few researchers have studied the competitive situation of SDV from a global perspective. In order to solve this problem, this paper apply a methodology of patent intelligence based on the advanced statistical methods and the social network analysis (SNA). Combining technology and organization, the paper sort out SDV technology comprehensively. A quantitative method is used to analyze complex structure of the technology, thus helping developers to systematically master SDV field and adjust R&D strategies. On this basis, this study evaluates the global competitive position and cooperation situation of innovators in this field. It can support the prediction of development trends, promote industry–university–research collaboration, and improve innovation performance.

The paper is organized as follows. Section 2 briefly reviews the development of SDVs, explains more technological details about them, also provides an overview of previous studies on the patent analysis and the SNA. In Section 3, we introduce the data and methodology. Section 4 provides the results of technological status, competition trends and cooperation trends identified based on global SDV patents. And in Section 5, the main conclusions, further research plans and limitations are discussed.

II. LITERATURE REVIEW

A. SDV

A typical SDV relies on the collaborative work of environmental perception, decision making, and execution to complete the transportation task [8]–[10]. SDVs can get information similar to our eyes. By using the LiDAR, the millimeter-wave radar, the ultrasonic radar, high-definition camera, and vehicle-to-vehicle communication (V2V) alone or together, adjacent vehicles, pedestrians, buildings, and transportation facilities are detected in real time, whereas the absolute position and the driving status are also provided by GPS and speed sensors, respectively. Subsequently, the processor processes the acquired data, plans a driving route, and makes decisions on vehicle behaviors. These decisions are transmitted to a series of controllers acting on gears, braking and steering through sensors. The execution unit feeds back to the other two units, and thus forms a closed loop [11], [12].

Obviously, the SDV is a complex technology system that integrates many fields such as mechanical engineering, automation, computer science, communication and AI. For a better exchange and the standardized management, in 2014, the Society of Automotive Engineers (SAE) in the United States divided the SDV into six levels, which is based on 'who', 'when' and 'do what', which also has been accepted by most experts. According to this standard, L0 is a stage that completely depends on human drivers. In L1 and L2, some automation units are added to vehicles such as Adaptive Cruise Control (ACC) and Automated Parking System (APS). This low-automatic SDV can also be called an Advanced Driving Assistance System (ADAS). However, the status of the human driver as the protagonist is not changed. When the SDV enters L3, monitoring driving environment will be handed over to the car for the first time. After L3, the system will perform all dynamic driving tasks, and the human driver only needs to intervene when some emergencies occur. This intervention will gradually decrease as the SDV steps to a higher level until the full automation in L6. So far, the SDV that meets L1 and L2 is very popular, and L3 and L4 also do not seem to be far away. For example, BMW has previewed 'BMW Vision iNext' in 2018, which is L3 autonomous, with L4 functions technologically available.

B. PATENT ANALYSIS

The patent literature is the largest source of technical information in the world, which includes more than 90% of inventions [13]. While, due to the expensive procedure in patent application and maintenance, the patent also embodies the economic value and the competitive advantage of an enterprise [13]. Hence, the patent analysis has long been considered as an important part of CTI in order to manage R&D activities, explore competition and cooperation, and make industrial policies [14].

A patent includes the inventor, applicant, patent classification codes, claims, and so on. In the patent analysis, some scholars collect information by the statistical description of patent data, in order to obtain significant information on technologies. Zhang *et al.* [15] design a technological map of the offshore wind power in China by counting regional distributions, applicants, and major patent classification codes. They find the competitive advantages of different provinces and thus emphasize improving the imbalance of development by strengthening cooperation. The use and diffusion of important technologies can be identified through the analysis of social network based on patent citation data [16], [17]. Additionally, a model based on the patent renewal period for evaluating the patent value is proposed, which helps in observing the narrowing gap between the developed and developing countries in core technologies. Yang [18] adopts the technology life cycle (TLC) theory and identifies the current life cycle stage of graphene technology.

Patent statistics like these can provide a lot of valuable information but ignore the links between organizations and technological subsystems, which cannot be compatible with the globalization of R&D cooperation and the complexity of technology. Fortunately, social network analysis (SNA) can improve these shortcomings and obtain more details from patents. It is considered an excellent tool to explore the communication (edges) between actors (nodes), and it has been used to describe interpersonal relationships or international trades [19]. In recent years, the SNA has played an important role in the patent analysis in identifying collaborative creativity, and explaining complex technological structures [20], [21].

For instance, Guan *et al.* [22] establish a cooperation network at a national level using all utility patents granted by the United States Patent and Trademark Office (USPTO), and then evaluate the evolution of international cooperation by the degree centrality and the betweenness centrality. Liu *et al.* [23] employ this framework in a smart grid field in order to show different types of cooperation relationships. They visualize the result by using the Gephi software, in which the dominant position of enterprise-enterprise cooperation is clearly demonstrated.

In addition to studies on the knowledge structure in the technological system, other studies seek to apply the patent classification co-occurrence network. In this network, nodes represent classification codes, among them the United States Patent Classification (USPC) and the International Patent Classification (IPC) are most commonly used [24], [25]. These nodes are linked by a tie when they occur together in one patent, and the strength of a tie represents the level of coupling [26], [27]. Yayavaram *et al.* [28] develop a 3-digit USPC co-occurrence network and split the semiconductor industry involving 400 technology classes into the following three clusters: digital processing systems, communications and networks and semiconductor devices and manufacturing. They believe that this kind of decomposition based on the SNA is valuable which can inspire more innovations. Leydesdorff *et al.* [29] downloaded more than 10,000 patents under the Patent Cooperation Treaty (PCT), employed IPC co-occurrence networks in 3- and 4-digit code levels, respectively, and confirmed that 4-digit level is a better option which is more informative and effective in the technological makeup. Chang *et al.* [30], [31] carried out this method on the 5G technology patents and forecasted hot R&D themes by referring to the centrality of each IPC. Yoon *et al.* [21] carried out this method on the Electronic Skin technology and traced the evolving trends and technology position in this field. This hybrid method is found to be feasible and effective in reflecting competition and cooperation and clarifying the confusing interdisciplinary structure of technology, which can perfectly meet our requirements. In this study, we employ this approach on SDVs in worldwide; especially the cutting-edge technologies that emerged in the recent period. It aims to support governments, enterprises, research institutes in recognizing the competitive situation in this field, finding new investment opportunities in time and also filling the research gap in the patent analysis.

III. METHODOLOGY AND DATA

The purpose of this study is to obtain CTI in the SDV field and the framework is shown by the flowchart, as illustrated in Figure 1. For a start, patent research includes three steps: choosing a database, setting down the retrieval strategy and filtering out the noise. After that, the initial patents for analysis are downloaded in batches. According to the technical innovation theory, there is a significant interaction between technological innovation and organization. Accordingly, it is necessary to conduct patent analysis from this two aspects in this study [32], [33]. Regarding technology, technical topics and R&D hotspots are identified in the given field. And the active competitors, their competitive advantages in each topic and the inter-organization cooperation are also fund. More explanations are in the subsequent paragraphs.

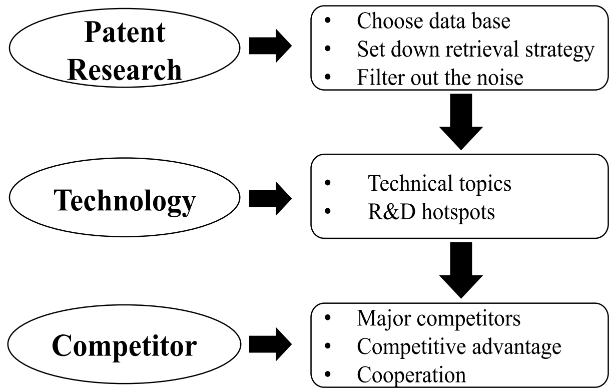


FIGURE 1. The framework of the research process.

A. DATA SOURCES

Accurate data is the premise of the patent analysis, which requires a suitable database and a retrieval strategy. In this study, we select the 'Derwent Innovation Index' (DII) as the data source. DII contains more than 11 million patent records from major countries in the world and supplies information on patent families, IPC classification codes, patent applicants, etc. Besides, abstracts are rewritten by experts to highlight the main points of innovations, and a standardized assignee name code is assigned to each patentee. All of the above factors provide a great convenience for users.

The next step is to plan the retrieval strategy. After reading and summarizing a large number of papers and books, branches in SDVs are defined and relevant elements such as keywords and IPC classification codes are extracted. Referring to the rules of DII, the formula is finalized and executed. The application date is limited to the period from 2014 to 2019, which is consistent with the focus on R&D hotpots in this study, though it also controls the data size. Finally, irrelevant patents and incomplete records are removed manually, and 68,960 patents are obtained for the in-depth analysis. For the search formula, see Appendix A. With the globalization of technology, patentees often apply for patents for the same technical content in multiple countries in order to protect their innovations to a greater extent. We extract the patent distribution country information from the patent application numbers contained in the same patent family. Therefore, the number of patent distributions in Figure 2 is greater than that of patent families. After the statistical analysis of this patent data, from Figure 2 we can find that patents of self-driving vehicles (SDVs) are mainly distributed in China (CN), the United States (US), Japan (JP), Germany (DE), South Korea (KR),

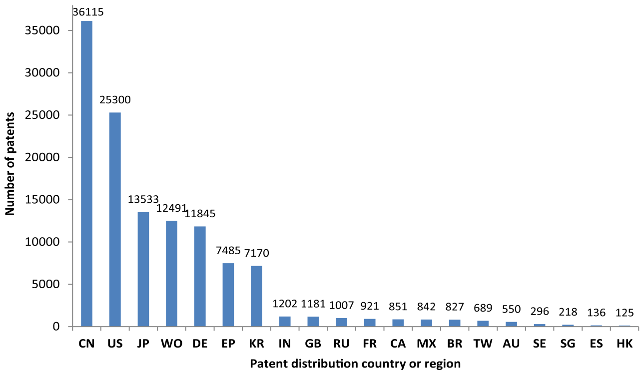


FIGURE 2. Global patent distribution in self-driving vehicles (SDVs).

the World Intellectual Property Organization (WO), and the European Intellectual Property Organization (EP).

B. TECHNICAL PERSPECTIVE

After data collection and preprocessing, the analysis from a technical perspective is considered the main task in the next part. An improved co-occurrence network of IPC codes is conducted, whereas the 6-digit IPCs are used to provide a more fine-grained analysis [34], [35]. Then, patents are clustered using Modularity measure, so that R&D topics and intricate connections among them are identified. The statistical description of the IPC classification codes is listed, which represent the technology fields included in SDVs. Besides, to obtain more details, the high-frequency words in each topic are extracted separately from the titles of relevant patents, and meaningless words such as vehicle, self-driving car, and method are manually wiped out, which can help improve the accuracy of our work. In many previous studies about patent co-classifications, the value of the tie between node pairs is equal to the co-occurrence frequency of the two IPCs. However, it ignores the intensive quantity of patents in certain categories. For example, there are 300,989 patents whose IPC contains 'B62D' (motor vehicles; trailers) in the DII database, whereas the number of patents containing 'A43B' (characteristic features of footwear; parts of footwear) is 93,542. (search date: August 1, 2020; time span: all years) [36]. This uneven distribution distorts the clustering results and causes negative effects on the analysis [36], [37]. In order to solve this problem, we replace the co-occurrence frequency with the Jaccard index in this study. The Jaccard index between IPCi and IPCj is calculate as:

$$R\_{ij} = R\_{ji} = \frac{n\_{ij}}{\left(n\_i + n\_j - n\_{ij}\right)} \times 100\% \tag{1}$$

Among them, n_{ij} indicates the number of patents co-occurring in the technical field i and the technical field j, n_i indicates the total number of patents with IPCi, and the n_j indicates total number of patents with IPCj.

C. COMPETITOR's PERSPECTIVE

The main objective of this section is to monitor the role of innovation subjects in the industry. By counting the number of patent applications, the most active competitors are detected. Then, the competition of enterprises is described the following by two indicators: the Relative Technology Advantage (RTA) index reflects the relative technological advantage of a firm, which is defined as:

$$RTA_i = \frac{P_{ij}/P_{iT}}{P_{Nj}/P_{NT}} \tag{2}$$

where the nominator is the share of a firm's patent applications in a certain R&D topic over its total patents, the denominator is the share of total patents in the topic j over the patents in all topics. i represents the firm under consideration, N represents all firms, j represents the R&D topic under consideration, T represents all R&D topics.

International Business Potential (IBP) is an indicator to measure a firm's performance in exploring international markets. It is calculated as:

$$IBP_i = \frac{TN}{P_{iT}} \tag{3}$$

where TN is the number of transnational patents in enterprise i, including patent applications filed at the European Patent Office (EPO) and international patent applications filed under the Patent Cooperation Treaty (PCT) [38], [39].

At the macro level, the following three indicators are used to describe the global cooperation network in the given field: network density, network centralization and average distance among nodes. The network density is the ratio of the actual number of ties to the maximum number of possible ties in a network. A higher network density indicates a closer association among actors [40]. Network centralization is a measurement of the overall cohesion or integration of the network. The network has a tendency to concentrate to a certain point if it has a higher network centralization. The average distance reflects the efficiency of exchanging information, a greater distance implies a longer time when the information diffuses in the network. At the micro level, centrality determines the value of a certain actor [41]. In this study, Degree Centrality, Betweenness Centrality and Closeness Centrality are adopted to evaluate the position of competitors. Degree Centrality is the total number of ties between a certain node and others, which reflects its ability of radiation and infiltration [42]. As a supplement, the weighted Degree Centrality is also given. It counts the frequency of connections among different nodes, which reflects the strength of cooperation. Betweenness Centrality of a node is defined as the frequency it appears in the shortest routes linking other node pairs in the network. A node with the high Betweenness Centrality plays the role of a broker or a gatekeeper between nodes; in other words, it is considered as a transfer station that controls information from different categories [43]–[45]. As for Closeness Centrality, it is the sum of the reciprocal distances from a certain node to all other nodes, reflecting its ability to disseminate information [46]. Centrality is not efficient when used alone because a node's influence highly depends on the attributes of the its neighborhood [47], [48]. To solve this problem,

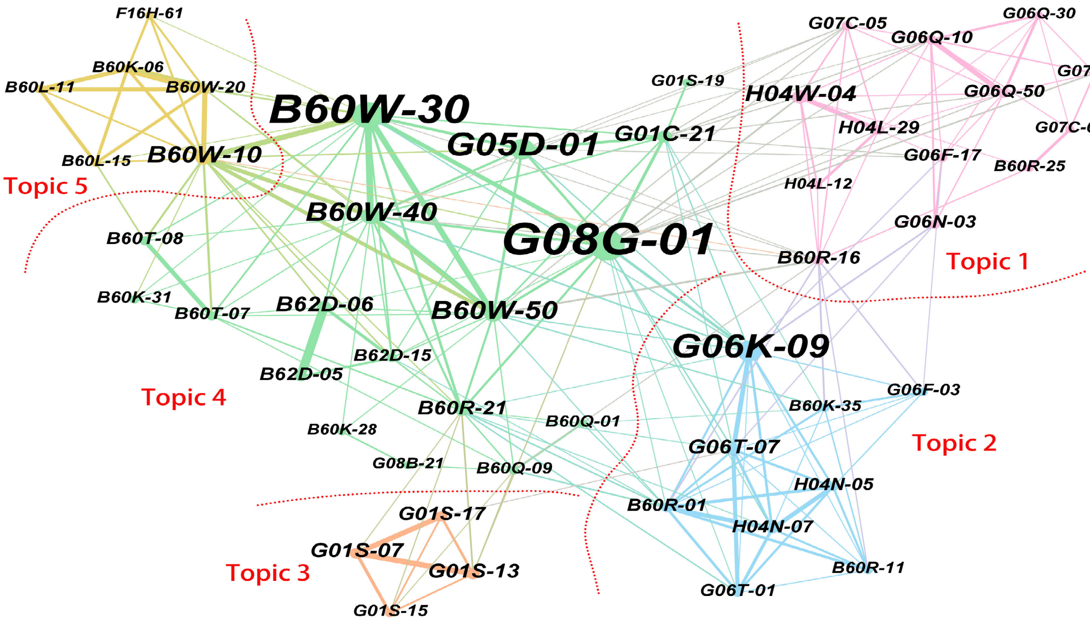


FIGURE 3. IPC co-occurrence network (Jaccard index > 0.065).

TABLE 1. Major IPC classifications in SDV (TOP 10).

IPC	Technological Field	Frequency	Degree Centrality	Topic
G08G-01	Traffic control systems for road vehicles	20611	46653	4
B60W-30	Purposes of road vehicle drive control systems not related to the control of a particular sub-unit, e.g. of systems using conjoint control of vehicle sub-units, or advanced driver assistance systems for ensuring comfort, stability and safety or drive control systems for propelling or retarding the vehicle	17869	50026	4
G06K-09	Methods or arrangements for reading or recognising printed or written characters or for recognising patterns, e.g. fingerprints	13034	28141	2
G05D-01	Control of position, course or altitude of land, water, air, or space vehicles, e.g. automatic pilot	12545	26011	4
B60W-40	Estimation or calculation of non-directly measurable driving parameters for road vehicle drive control systems not related to the control of a particular sub unit, e.g. by using mathematical models	8530	29336	4
B60W-50	Details of control systems for road vehicle drive control not related to the control of a particular sub-unit, e.g. process diagnostic or vehicle driver interfaces	7867	27878	4
B60W-10	Conjoint control of vehicle sub-units of different type or different function	6233	21931	5
H04W-04	Services specially adapted for wireless communication networks; Facilities therefor	5742	10250	1
G01C-21	Navigation	5136	15533	4
B62D-06	Arrangements for automatically controlling steering depending on driving conditions sensed and responded to, e.g. control circuits	4824	4824	4

the PageRank value based on tie strength is used to identify the most influential enterprise in the cooperative network in this paper. PageRank is an algorithm based on random walk and multiple iterative operations, so that the capabilities of neighborhoods are taken into consideration when calculating the influence of nodes [49], [50].

IV. RESULTS AND DISCUSSIONS

A. TECHNICAL TOPICS AND R&D HOTSPOTS

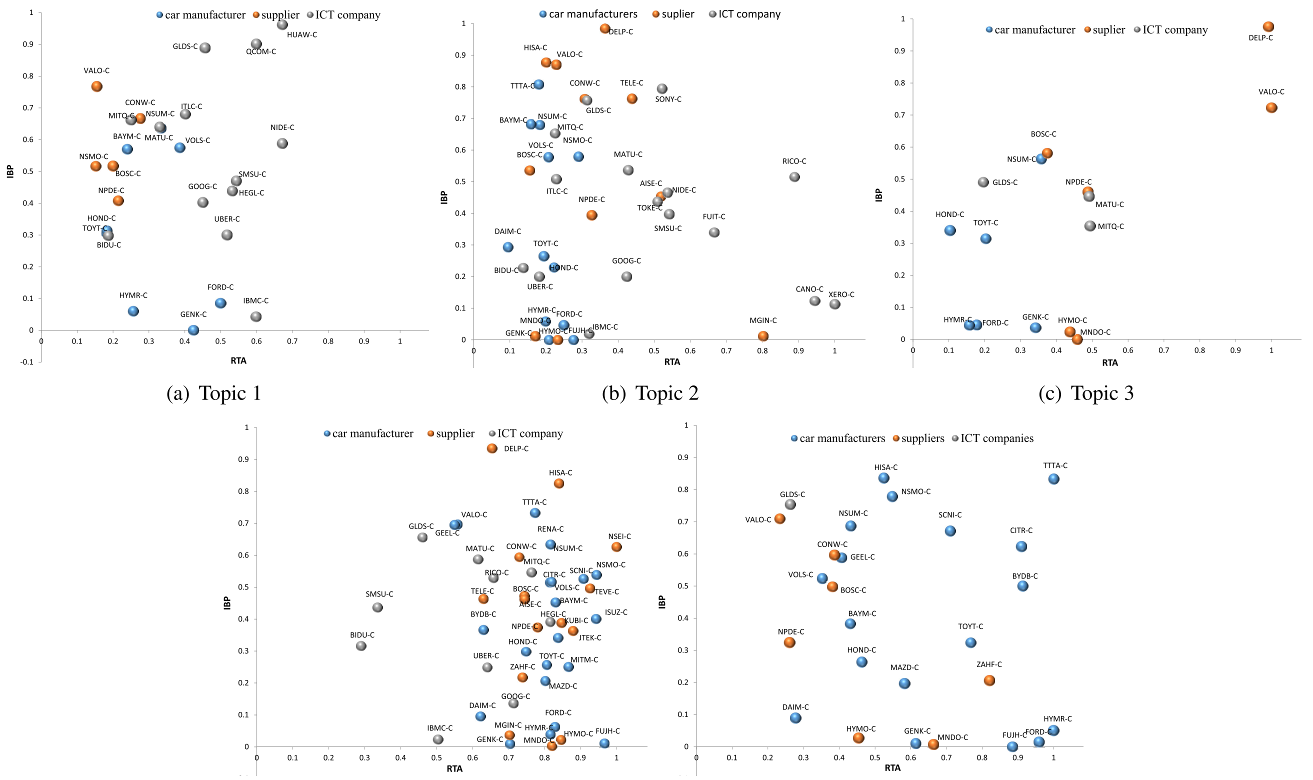
In order to obtain a systematic view of R&D topics and the relationship between them, the IPC co-occurrence network is constructed and is clustered into 5 categories by using the Modularity measure. The network and its characteristics are detailed in Figure 3 and Table 1. Topic 1 is primarily related to the remote activation and supervision in transportation, for example, the platform used to manage traffic flow, license plates, or parking spaces in parking lots. It also includes some auxiliary functions such as driverless taxi and unmanned shopping service. Topics 2 and 3 are related to environmental perception in SDVs. Topic 1 is primarily related to the remote activation and supervision in transportation, for example, the platform used to manage traffic flow, license plates, or parking spaces in parking lots. The most frequent words are "image", "terminal", and "server", which appear 1744 times, 1333 times and 1264 times respectively. It can be concluded that the collection of data from users, vehicles and the environment, and the devices used to support the communication between the user terminal and the telematics terminal are hotspots in R&D. Other hotspots include "message" (873), "communication" (848), "parking space" (744), "node" (595), "management system" (528), "platform" (487) and "neural network" (455). Topic 2 contains the display apparatus, memory, and the processor for capturing the image data of vehicle interior and surroundings; in this scheme, the camera plays the primary role. Topic 3 is another way of using the radar system, in which the LiDAR and the millimeter wave radar are the key elements. As compared to the camera-based scheme in topic 2, the high cost of the radar system has always been an obstacle to the widespread adoption in SDVs. However, many devices that assist in data transcoding and processing in that scheme can be removed. This can also be confirmed by the frequent words in the two topics. In topic 3, high-frequency words include "data" (1008), "radar" (802), "direction" (502), "controller" (469), "surface" (410), "circuit" (385), "antenna" (342), "wave" (327), "ultrasonic sensor" (325) and "beam" (282), most of which are about features or parts of radar. On the contrary, "model" (1051), "point" (928), "controller" (922), "line" (640), "map" (607), "feature" (516), "light" (499), "side" (406), "surface" (399), "response" (370) are top ten high-frequency words in topic 2. It seems that the "model" is more important than the camera itself. For example, deep learning models (such as US2016217335-A1, US2019025773-A1), Bayesian models (US2016209511-A1, etc.), Markov models (US2015042808-A1, US2015042808-A1, etc.) are all tried to be applied in camera-based vision system to improve performance in terms of calibration, processing and response. Topic 4 is closely related to the vehicle control system. According to road conditions and traffic flow, the SDV operates the components of the vehicle, performs CCS, lane keeping assistance systems (LKAS), turning, and other actions to switch to a proper mode. In this process, the vehicle needs a superb ability to process multi-source data, which causes "image" (3495), "object" (3411), "location" (1676), "control apparatus" (1576), "trajectory" (1090), "wheel" (1885), "angle" (1422), and "force" (1194) become popular words. And there are other high-frequency words including "parking" (2259), "steering" (876) and "acceleration" (714), which are related to execution. Inventions in topic 5 are related to about the automobile engines. In detail, hybrid engines, electric vehicles and management of energy storage means are the main content. As for the keywords, "torque" (1213), "engine" (897), "information" (843), "motor" (729), "hybrid vehicle" (561), "sensor" (524), "control apparatus" (498), "force" (414), "clutch" (385) and "power" (358) are in the top ten, which provide more information about this topic.

For more details, the R&D hotspots and fronts are listed in Table 1. As can be seen from the table, most IPCs are associated with topic 4, which illustrates the core position of the related technologies. G08G-01 and B60W-030 demonstrate the highest frequency and Degree Centrality. These two IPCs mean analyzing traffic movement, controlling traffic signals and some automatic actions of vehicles. They are considered hot R&D areas and key technologies. Still in topic 4, the control and adjustment of the 2D position or the 3D position of the vehicle (G05D-01), the change of driving status (B60W-50), (B60W-40), (B62D-06), (G05D-01) including braking, steering, acceleration and deceleration, etc., are still also valuable and important.

Monitoring the driving environment is considered a difficult task that must be faced in R&D when entering L3 and beyond. G06K-09 contains identifying status of drivers or passengers and collecting road information during transportation, which is regarded as important technological field by competitors, with a high degree centrality as well. B60W-50 is also related to the control system. Based on the data in our study, it appears more in topic 5, and represents the management of energy storage and fuel cells. As we know, because of the strict laws on exhaust emissions all over the world, improving the automobile engine has become a valuable task in the automobile industry.

According to the number of patent citations and opinions of experts in this field, high-value patents are selected, which aims to use these outstanding technical solutions to stimulate more innovations. Most of them are related to vehicle control systems, and belong to more than one topic. US2016339959-A1 from LG is about an autonomous emergency braking (AEB) which gives a warning alarm to a driver about an obstacle ahead and autonomously operate the brake when the driver does not react to the warning alarm. US2015070160-A1 from Volvo is a detecting arrangement for monitoring a vehicle driver and evaluating a vehicle driver's readiness to assume an act of driving a vehicle. Their main content is to provide a reference for the driver's decision and falls within the scope of L0 SDV. General Motors Co. Ltd's patent US9229453-B1 is a typical innovation in L1 of SDVs. In this patent, the car monitors the lane center of a roadway lane by combining cameras and sensors, allows the vehicle to travel along the roadway lane and automatically steer along the center line of the road. Further, WO2015024616-A1 filed by Audi and CN104477167-A filed by Zhejiang University contain a driver assistance system which allows switching to another operating mode if some specific driving situations are satisfied. In other words, they have achieved a low-automated SDV that meets the L1 and L2.

Some patents only focus on a certain module of SDVs. In Sony's patent WO2016156236-A1, an algorithm for improving object detection is adopted, the car captures current and past data frames from environment by a recurrent neural network. CN106250812-B is about Rapid R-CNN depth neural network based vehicle type identifying method. Also about road monitoring, US9286520-B1 of Google relates to detecting real-time road flare using a multi-pixel method. In terms of vehicle communication, a patent submitted by Google US9008890-B1 discloses a communication standard directed towards intelligent transport system. And CN105225521-A from Chongqing Dingcheche Technology is about a parking management system based on the Internet of Things, in which the cloud platform receives user information from mobile terminals and implements limited resource



(a) Topic 1 (b) Topic 2 (c) Topic 3

(d) Topic 4 (e) Topic 5

FIGURE 4. **Competitive advantages of enterprises under each topic.**

optimal value estimation. Regarding the energy consumption of SDVs, a patent from Ford US9097549-B1 proposes a scheme to maximize fuel efficiency through reasonable planning of routes, in which the navigation system and remote server are combined. In the patents related to interaction of multiple vehicles, WO2015169204-A1 filed by Huawei contains a vehicle scheduling server enables scheduling the cars according to the current position information, current road condition information and planned route information about several autonomous vehicles. US9079587-B1 from Ford is a method for facilitating autonomous control in dense vehicle environment, a virtual map of probable environment using information from two other vehicles is the most important content.

B. COMPETITION AND COOPERATION

First, we list the most active enterprises in SDVs. In terms of the number of patent applications, Toyota (TOYT-C) holds the top spot in patent applications with its 2555 patents, and far surpasses Ford (FORD-C) (1868) and Bosch (BOSC-C) (1742), which are ranked in the second and the third place, respectively. In addition, Denso (NPDE-C), Hyundai (HYMR-C), Honda and General Motors Co. Ltd (GENK-C) also have more than 1,000 patent applications. According to their country origin, most of the applicants from Japan are in top 10, including Toyota, Denso, and Honda. While the first two of them enter top 5, which reflects the powerful R&D activities of Japan in SDVs, and the United States and Germany have two applicants as well. Furthermore, in the first-tier competitors in SDVs, car manufactures such as Toyota, Ford, Hyundai, Daimler, etc. still have apparent advantages. They are working hard to conform to the new trend, maintain their positions in the automotive industry. Meanwhile, Bosch, Denso, and Valeo are active competitors, these important automotive suppliers also have an important position in SDVs. Unlike all the above-mentioned enterprises, Baidu Online Network Technology Co. Ltd (BIDU-C) has always been known for its Internet search service. In 2013, Baidu established the smart car business dedicated to providing big data platforms and software services for SDVs, aiming to explore new opportunities and growth points.

Then, the competitive advantages of enterprises under each topic are identified by calculating IBP and RTA. In order to emphasize the main information, all the enterprises with more than 50 patents under a certain topic are shown in Figure 4. In general, members in the first-tier are comprehensive and pay more attention to key technologies, but they still need to improve in expanding the international market. Meanwhile, some other companies are considered experts in these particular fields.

Regarding the remote activation, supervision in transportation, and auxiliary functions of SDVs (Figure 4(a)), companies in the information and communications

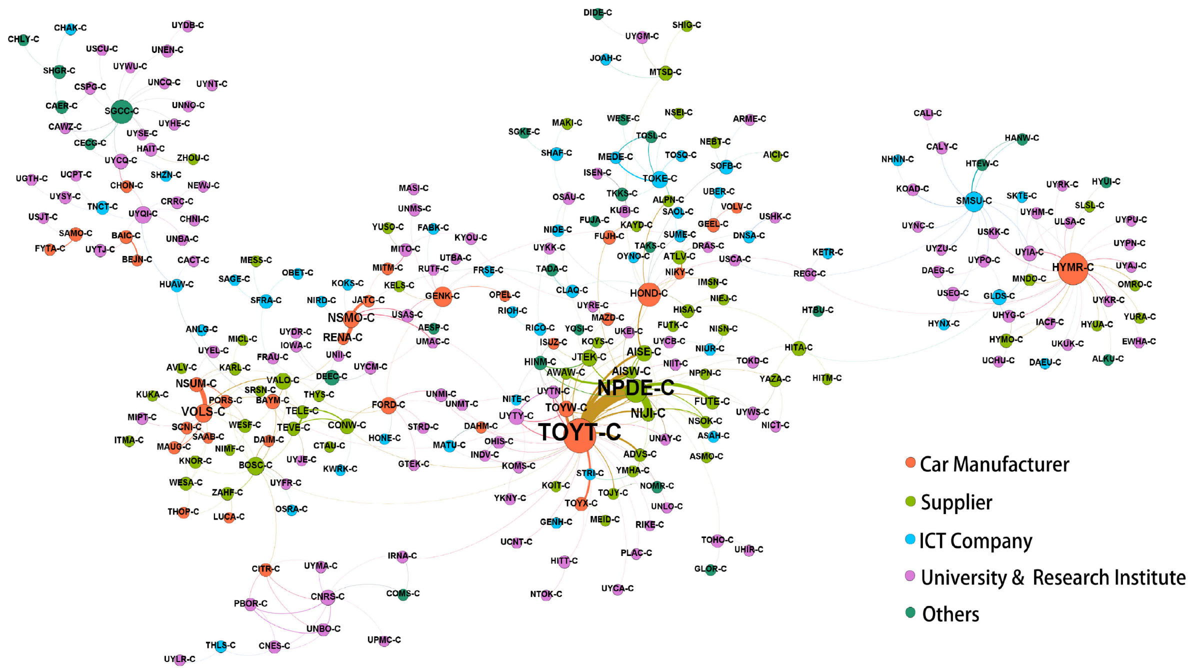


FIGURE 5. Patent cooperation network.

technology (ICT) have exhibited outstanding performances thanks to their achievements in communication infrastructure, big data platform, and cyber security, especially Huawei (HUAW-C), Qualcomm (QCOM-C), NEC (NIDE-C), etc., show obvious competitive advantages in this topic. They are world leaders in telecommunications and are expanding 5G's application scenarios to car communications. Taking Huawei as an example, it is building a seamless interconnection platform through Mobile Data Center (MDC), Telematics BOX and Huawei Cloud. Huawei is not a vehicle manufacturer, but its expertise in the ICT field may help vehicle manufacturers to improve their capabilities. Qualcomm carries out a similar strategy to improve safety and management for the intelligent transportation system, its C-V2X technology is being tested on a large scale.

In the camera-based environmental perception unit, suppliers and ICT companies have exhibited excellent performances, in which Ricoh (RICO-C) and Hitachi Automobile Systems Ltd (HISA-C) are the most valuable competitors. They not only focus on R&D, but also have a wide layout in the international market. In addition, the outstanding technical capabilities of Canon (CANO-C) and Fuji Xerox (XERO-C) are also worth noting. In contrast, the environmental perception scheme based on the radar system attracts fewer enterprises, Delphi (DELP-C) and Valeo (VALO-C), two well-known suppliers, have demonstrated notable competitive advantages in this topic.

The automobile control system (topic 4) is the hottest topic. As shown in Figure 4(e), all three types of enterprises appear in large numbers. Most of them, such as Toyota (TOYT-C), Ford (FORD-C), General Motors Co. Ltd (GENK-C) and Hyundai (HYMR-C), heavily invest in the R&D of the related technologies but do not pay adequate attention to the international market. While Volvo Car Corp. (VOLV-C), Man Truck & Bus AG (MAUG-C), Wabco Co Ltd (WESA-C), etc., have competitive advantages both in the market and technology, so as to stand out from so many enterprises.

As far as the automobile engines are concerned, car manufacturers dominate the competition in this topic, in which Jaguar Land Rover Co. Ltd (TTTA-C) is considered the best representative. At the same time, Ford, Toyota, Hyundai, etc., have also invested more in the R&D of the related technologies, but are placed at massive disadvantages in market development, and manifested as a small IBP value. As a well-known new energy vehicle company, BYD Co. Ltd (BYDB-C) also has a good position. At present, electric-operated cars have entered the market on a large scale, and the integration of new power and automation may become an important content in the automotive industry in the near future. Not only BYD, NIO, Tesla, and many other new energy vehicle manufacturers have all considered this integration as their core strategy.

Cooperation between enterprises will be analyzed by the patent cooperation network. Due to space limitations, only the main clusters are shown in Figure 5. From the overall dimension, the characteristics of the network structure are captured through number of ties, network density, network centralization and average distance among nodes. In the global SDVs patent cooperation network, the number of ties is 380, and the network density is equal to 0.0102. It can be

TABLE 2. The Centrality and PageRanks of enterprises (TOP 20).

Lable	Patent Assignee	Centrality in Patent Cooperation Network				PageRanks
		Degree	Betweenness	Closeness	Weighted Degree	
TOYT-C	Toyota Jidosha Kk	37	0.4049	0.2747	408	0.0593
NPDE-C	Denso Corp	20	0.1350	0.2554	344	0.0463
HYMR-C	Hyundai Motor Co	26	0.1729	0.1866	61	0.0364
VOLS-C	Volkswagen Ag	12	0.0562	0.2121	99	0.0230
SGCC-C	State Grid Corp China	13	0.0828	0.1192	18	0.0199
NSMO-C	Nissan Motor Co	8	0.0767	0.2274	103	0.0187
SMSU-C	Samsung Electronics Co	12	0.0832	0.1748	33	0.0175
HOND-C	Honda Motor Co	17	0.3266	0.2433	42	0.0165
NSUM-C	Audi Ag	6	0.0152	0.1910	69	0.0158
NIJI-C	Nippon Jidosha Buhin Sogo	5	0.0016	0.2280	122	0.0150
GENK-C	Gm Global Technology Inc	11	0.1082	0.2059	18	0.0123
AISE-C	Aisin Seiki Kk	9	0.0926	0.2514	61	0.0120
AISW-C	Aisin Aw Co	3	0.0003	0.2289	80	0.0105
TOKE-C	Toshiba Kk	7	0.0425	0.1679	30	0.0100
BOSC-C	Bosch Gmbh Robert	12	0.1846	0.2466	27	0.0099
UYCQ-C	Univ Chongqing	5	0.1381	0.1335	11	0.0097
TOYW-C	Toyota Chuo Kenkyusho Kk	10	0.0248	0.2475	68	0.0095
TELE-C	Conti Temic Microelectronic Gmbh	4	0.0181	0.2097	37	0.0094
RENA-C	Renault Sas	2	0.0081	0.2021	52	0.0089
CNRS-C	Cent Nat Rech Sci	8	0.0326	0.1902	25	0.0089
TEVE-C	Continental Teves & Co Ohg Ag	5	0.0249	0.2190	34	0.0089

called a sparse network refer to the previous papers [51]. The network centralization is 0.127 and average distance among nodes is 5.939, which proves the fact that the coupling of the cooperative network is loose with low efficiency in knowledge flow. In order to obtain more information about the actors in this network, three types of Centrality and PageRank value of nodes are measured. As shown in Table 2, Toyota has always ranked first in terms of Degree Centrality, Betweenness Centrality and Closeness Centrality, which indicates its structurally advantageous position in the global patent cooperation network. More precisely, it could be regarded as one of the informal leaders of the group [52]. Toyota also obtains the highest PageRank value among all enterprises, confirming its powerful influence from another aspect. It can be clearly seen that Toyota establishes extensive cooperation, including many partners with complementary advantages or influential capabilities: Ricoh (RICO-C) and AISIN SEIKI Co. Ltd (AISE-C) have outstanding performance in topic 2, and Denso is a good expert in topic 3. It greatly makes up for Toyota's failings in SDVs. Besides, Toyota cooperates with the Tokyo University (UYTY-C) in Japan, the Max Planck Institute (PLAC-C) in Germany, the Ohio State University (OHIS-C), and the University of Connecticut (UCNT-C) in the United States based on its three R&D centers, which reveals its determination to enhance basic research. It can be found from the result that most of the actors with major influence are car manufactures. They have similar features in cooperation compared with Toyota, which shows diversification and complementarity to a certain extent, but most of the partners are limited in the domestic area or other nearby regions. In addition, Samsung is the only ICT company in the top ten. Samsung has no obvious advantage in the number of patents, but the multiple partnerships (demonstrated by a higher Degree Centrality) including actors with high influence such as Hyundai Group improves its ranking effectively.

V. CONCLUSIONS

As a complex system integrating many advanced technologies, the SDV has emerged as a new driving force for the automotive industry. In this article, we retrieved 68960 patents from the DII database and used a hybrid method based on the patent statistics and the SNA to reveal R&D topics and hotspots, monitor competition and cooperation.

Firstly, the technical complexity of SDVs is reflected intuitively and comprehensively, which requires inventors to pay more attention to patent portfolios for amplifying their competitive advantages. The relevant technologies in SDVs can be classified into five R&D topics: remote activation and supervision in transportation, camera-based perception unit, radar system, vehicle control system and automobile engines. It can be noticed that "image" and "data" are highly repeated in several topics. It must also be mentioned that many other popular words such as "location", "trajectory", "neural network", "model", etc. are also highly relevant to data, which reveals that data is decisive for researchers. Moreover, the vehicle control system is in the most critical position among the five topics. And image, object, parking, wheel, location, control apparatus, angle, force, trajectory, steering and acceleration become the high-frequency words in this topic. Besides, we conclude that data has become an important intangible asset that will lead to new forms of monopoly and competition. It is meaningful to establish a global management system for data protection, sharing and transaction, which requires governments, enterprises and international organizations to work hard together.

Secondly, division of labor in manufacture of automobile and internet technology fusion in SDV field have opportunities to break the industry segmentation, eliminate market barriers, innovate the system, production mode and application mode and enhance the innovation chain and value chain of the entire industry. As for the innovation subjects, most active companies focused on Japan, the United States and Germany, which reflects the technological strength of the developed countries to a certain extent. According to the types of these subjects, more than half of the most active competitors are car manufacturers. Long-term accumulation brings them excellent independent innovation capabilities in a wide range of R&D topics, which allow them to still maintain their status in the current period. Meanwhile, it cannot be ignored that the potential threat comes from automotive suppliers and ICT companies, especially the former. For many decades, the automobile industry had shown a highly concentrated feature. And it led to enormous know-how flowing to suppliers, which weakened the position of car manufacturers [53], [54] in the market. Now, the new industry revolution causes a quick response from many suppliers. They are active and have good performance in patent applications on some specific technical topics. This fact may lead to further value migration in the automobile industry and make suppliers the most powerful challengers to break the established order. As newcomers in the industry, ICT companies are outstanding in business and platform, as well as in environmental perception modules. They are a potential new faction to grab the market share in SDVs.

At last, in the SDV field, increasing technological complexity calls for a new model based on open innovation, in which more accessible and efficient cooperation will be a crucial factor affecting the future of the industry. As far as cooperation is concerned, although some large groups that include multiple partnerships have emerged, the global cooperation network of SDVs is still at an early stage of development. It is loose and inefficient due to the lack of international cooperation and low-level communication between leaders, which is very negative for the commercial-scale deployment of SDVs. At the micro level, Toyota has the highest influence and plays the role of an informal leader, which should owe to its cooperation strategy based on openness and complementary advantages. In addition, ICT companies, as the undertakers of new infrastructure such as 5G base stations and data centers, need to urgently strengthen their connections with other companies. Their technologies for car communications always require the large-scale testing before implementation, so that a wider alliance can help improve the performance more quickly, and further, inspire more innovations. In the germination period and growth period of emerging technologies, both technology and the market shows great uncertainty, so cooperation is a proper way to reduce investment risks and improve innovative performance. So the SDV field needs more "Toyota" to integrate partners from different industries and even from different countries, and they will certainly benefit from them. In summary, the above findings are valuable to help the government, industry and academia to systematically understand this technology and make a series of well-directed strategies.

Despite the above-discussed findings, there are still several limitations to our work. Due to the rapid development in SDVs, the dynamic evolution of innovation and changes in competition and cooperation should be continuously monitored in the future. Besides, richer data sources such as research articles also need to be considered for a more sustainable analysis method.

APPENDIX

A. PATENT RETRIEVAL OF SELF-DRIVING VEHICLES (SDV)

Patent search formula of self-driving vehicles (SDV) constructed in this paper is as follows: ((IP = (H04W-004/44 OR H04W-004/46 OR B60W-030/16 OR B60K-031/00 OR B60T-008/1755 OR B60W-030/06 OR B60W-030/08 OR B60W-030/14 OR B60W-030/16 OR B60W-030/17 OR B60W-030/085 OR B60W-030/095 OR B60W-030/16 OR B60W-030/165 OR B60W-030/18 OR B62D-006/00 OR B60W-030/00 OR B60W-040/00 OR B60T-008/175 OR B60T-008/176)) OR (TS = ((("5G") or ("fifth$generation") or ("5th generation")) and ("car" or "vehicle*" or "automobile*")) AND IP = (H04W-004/02 or H04W-036 OR H04L-067)) OR (IP = (H04W-004/44 OR H04W-004/46 OR G05D-001/02 OR G08G-001/0968 OR G08G-001/127 OR G01S-013/93 OR G01S-015/93 OR G01S-017/88 OR G01S-017/93 OR G01S-007/52 OR G05D-001/02 OR G01S-013/00 OR H04W-004/40 OR B60W-050/02 OR G05B-013/00 OR G05D-001/00 OR G05D-001/02 OR G06N* OR G06K-009/00 OR G06T-001/20 OR B60W-050/02 OR B60W-050/02 OR G08G-001/14 OR G01S-007/00 OR G01S-007/00 OR G01S-007/02 OR G01S-007/52 OR G01S-013/00 OR G01S-013/86 OR G01S-013/87 OR G01S-013/93 OR G01S-015/00 OR G01S-015/02 OR G01S-015/87 OR G01S-015/93 OR G01S-017/00 OR G01S-017/02 OR G01S-017/06 OR G01S-017/87 OR G01S-017/88 OR G01S-017/93 OR G01S-007/48 OR G06T-001/00 OR G06T-001/20 OR G06K-009/00 OR H04N-005/335) OR TS = ("visual sensor" OR "vision sensor" OR "machine vision" OR "light laser Detect*" OR "LiDAR" OR "LADAR" OR "Laser Radar" OR "millimeter$wave*" OR "MMW" OR "MM$wave" or "millimeter microwave")) AND TS = ("car" or "vehicle*" or "automobile*") NOT TS = ("AGV" OR "automat* guide* vehicle" OR "train" OR "ship" OR "boat" OR "plane" OR "aircraft" OR "UAV" OR "AUV" OR "ROV" OR "underwater" OR "aerial vehicle*" OR "arial vehicle*" OR "underwater vehicle*" OR "air vehicle*" OR "unmanned drone*" OR "unmanned aerial vehicle*") OR (TS = ("driverless car*" OR "driveless vehicle*" OR "unmanned vehicle*" OR "unmaned car*" OR "self-driv* vehicle*" OR "self-driv* vehicle*" OR "pilotless car*" OR "pilotless vehicle*" OR "automatic driv* car*" OR "automatic driv* vehicle*" OR "autonomous car*" OR "autonomous vehicle*" OR "autonomous driv* car*" OR "autonomous driv* vehicle*" OR "autonomic car*" OR "autonomic vehicle*") NOT TS = ("UAV" OR "AUV" OR "ROV" OR "underwater" OR "aerial vehicle*" OR "arial vehicle*" OR "underwater vehicle*" OR "air vehicle*" OR "unmanned drone" OR "unmanned aerial vehicle*" OR "tramcar*"))) NOT IP = (B61L*)

B. CONFLICTS OF INTEREST

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, 'Revealing technology innovation, competition and cooperation of self-driving vehicles from patent perspective'

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