The Impact of Competing Powertrain Technologies on the Formation of Automotive Innovation Networks

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Abstract--**The automotive sector faces a fundamental transformation due to technological change regarding low-emission vehicles. The simultaneous development of different alternative powertrain systems is a complex and expensive challenge for the whole industry. As the high risks and costs can be shared and complementary core competencies can be combined, innovation networks, representing a specific form of inter-organizational coordination, increase in importance. Based on network theory, we examine the institutional relationship of car manufacturers and suppliers to gain a better understanding of joint strategies.**

Our study contributes to the scientific discussion on patent analysis by developing an elaborate combination of patent classes and keywords. In this way, we create a highly valid dataset of over 71,000 patents consisting of four different powertrain technologies: internal combustion engine vehicles, hybrid electric vehicles, battery electric vehicles and fuel cell electric vehicles. We analyze the collaboration of different firms by extracting those patents that show a joint assignment of two or more assignees, leading to a total of 2,025 bi-lateral connections. This approach enables us to measure the spread of innovation networks over time and to reveal insights on the direction of partnerships and the role of certain actors within the network. Complemented by practice-oriented examples, our findings contribute to the understanding of automotive networks with respect to the ongoing and yet to be decided competition of powertrain technologies.

I. INTRODUCTION

The automotive industry was confronted with a major fraud case in 2015. The Volkswagen Group admitted the manipulation of software in several car models in order to report a lower output of nitrogen oxides (NO_x) in laboratory emissions testing. Thus, those car models were able to comply with US standards, which they otherwise would not have met. This case shows one of the challenges that original equipment manufacturers (OEMs) in the automotive industry face. Increasing government regulation concerning emissions require a large degree of innovative activity. Besides regulations, the automotive industry is confronted with further trends that cause multiple challenges. The intensity of competition constantly increases due to technological change, globalization, as well as changing markets and customer requirements. In order to have a leading position in the market and secure long-term success, OEMs – as well as their suppliers – need to (further) develop innovative products. This is of special importance in the so-called mega trends like automated driving, safety, connectivity, comfort and sustainability. The latter is strongly determined by incremental improvements of the internal combustion engine (ICE) on the one hand and the development of alternative powertrain technologies on the other hand.

The Volkswagen case shows that OEMs have reached the limit of their ability to make incremental improvements to the ICE in order to meet government regulations. Therefore, recently many carmakers have added a high-voltage battery to the ICE engine in order to reduce emissions (hybrid electric vehicle, HEV). Due to the limitation of fossil fuels in the long run, the HEV has to be assessed as a bridging technology. Therefore, an alternative technology will prevail that most likely uses electricity (battery electric vehicle, BEV) or hydrogen (fuel cell electric vehicle, FCEV) as its source of power. So far the outcome of this technological competition is unclear. One single firm is rarely capable of managing the complexity and necessary specialization for the development of several alternative powertrain systems [67]. To generate competitive advantages and reduce the individual innovative pressure for each firm, collaboration networks are created between different market players [69], [15]. Within these networks, the joint application of a patent by two or more firms is a frequent practice in order to secure the shared knowledge of a common innovative activity. By analyzing these jointly issued patents, much can be learned about the development of the ICE and alternative powertrain technologies in automotive networks.

In scientific literature, diverse contributions exist that deal with the occurrence of collaboration within different types of networks [3], [15], [21], [25], [48], [61], [70]. One of these types is the innovation network. Here, patents are often used as a proxy to investigate collaboration [11], [63], [65]. A limitation of most studies in this area is that they focus on a small number of firms, mostly OEMs. Therefore, the present paper uses an open search strategy that includes all OEMs and suppliers that hold a certain number of patents in the field of powertrain technology for cars. In total, we identified a highly valid dataset of 71,938 patents for the years 1990-2012. Based on a network-oriented theoretical approach, the goal of this study is to determine how far OEMs and suppliers use innovation networks. We therefore formulate two different research questions:

- *Which kinds of collaboration can be identified within the automotive industry regarding powertrain systems?*
- *To what extent does the technological change towards alternative powertrain systems encourage collaboration?*

To assess these questions, we divide the paper into three main areas. The *theoretical background* provides the reader with fundamentals of both collaborative innovation and the automotive industry. Within the *methodology*, we describe the processes of data collection and data processing, which ensure a highly valid and conclusive dataset. Finally, the *results and discussion* section shows the descriptive results and discusses different interpretations and implications.

II. THEORETICAL BACKGROUND

A. Relational View

The relational view [27] approach, developed by Dyer and Singh, can be seen as an extension of the Resource-based View [26]. A firm is no longer a closed entity but part of an inter-organizational exchange relationship due to the competitive advantages arising from common and collaborative work [27], [46]. This analysis focuses on interfirm activities and by doing so covers a long-neglected domain of strategic management research [19], [51]. Dyer and Singh see the advantages of inter-organizational relations in the creation of relational rents. These rents have the form of supranormal profits that cannot be achieved solely by one of the participating firms but arise only as part of the common idiosyncratic amounts from the specific collaborating partners. They are created when the participating network partners exchange resources, invest in cross-firm resource relations, use control and monitoring mechanisms that reduce transaction costs or realize an additional utility by the creation of synergetic combination of resources [24], [27]. Out of this fundamental view, Dyer and Singh derive four sources of competitive advantages from network-like relations: relation-specific investments, knowledge-sharing routines, complementary resources and capabilities, and effective governance [27].

Relation-specific investments in assets adapted to the particular collaborating partner enable the creation of efficiency advantages within and along the value chain [14], [57]. Thereby Williamson differentiates between site specificity, physical asset specificity, and human asset specificity [81]. Site-specific investments are understood as the agglomeration or spatial consolidation of firms into one region. Physical asset specific investments describe expenses in, for example, machines, tools and other measures that are coordinated with the respective partner. Human asset specificity arises when the participating actors of a network collect common experiences in long-term relations and by that create collective knowledge [29].

Knowledge-sharing routines lead to a knowledge expansion that serves as the starting point for the development of new innovation. Especially in technology-intensive and dynamic industries, like the automotive sector, the regular transfer of knowledge and the creation and reconfiguration of knowledge within the network can contribute to the achievement of competitive advantages compared to other non-collaborating firms [32], [61].

A third source of relational rents is located in the merger of **complementary resources and capabilities**. The uniqueness of the firm-specific resources of each participating firm is a necessary prerequisite, which means that acquiring these resources from outside the network is not possible. Only the combination of these distinctive and complementary portfolios enables the creation of rents that the firms are not able to realize on their own. The compatibility of the firms on an organizational level is a necessary condition and can contribute to increasing the relational rents [22].

A last aspect for the generation of competitive advantages is an **effective governance** that manages the network. Governance is a central role since it influences both the transaction costs and the willingness of the participating partners to engage actively in the creation of common value. To reduce the transaction costs and the risks arising from opportunistic behavior, the introduction of institutional frameworks and regulations is necessary. This is of highest importance, as an alternative use of relation-specific investments is often not possible so that incentive systems have to be established to reduce opportunistic behavior. Since formal contracts usually imply higher costs, the partners often fall back on informal agreements. These agreements mainly contribute to build up trust and a joint identity for the collaboration [18], [20], [28], [40].

In conclusion, the strategic goal of the participating actors is not the construction of a firm network, but rather the related reciprocal network access and the construction of resources and capabilities. Since strategic relevant resources are not available on the market and additionally are not allocated homogenously between the firms, an incentive can arise to participate in a network [37]. The relational view has been criticized for its mixture of resource, transaction costs, and behavioral elements without checking the applicability of the particular approaches [52]. Nevertheless, the relational view is well suited to investigate and explain the emergence of networks regarding the achievement of competitive advantages since both intra- and inter-organizational aspects of strategic resources are connected with network-oriented theoretical elements.

B. The Automotive Industry

The automotive industry is known for strong ties between firms. Starting in the 1990s, the success of Japanese OEMs keiretsu system [25], [28], [48] led to a strong integration of suppliers into the internal value chain of carmakers around the world [71]. Thus, the transfer of responsibilities intensified the manufacturer-supplier relationship. In Germany, currently 70% of created value can be attributed to suppliers [76]. OEMs strongly benefit from the collaboration with highly innovative suppliers. These firms often possess a technological advantage over the OEMs in their area of expertise and thus independently develop innovations and offer them to the manufacturers. This outsourcing enables the OEMs to reduce their complexity, to strengthen their technologic specialization and to reduce costs related to research and development (R&D) activities [68].

Within the last decades, the automotive industry ran through a strong process of concentration and is nowadays a highly consolidated sector. The strongest OEMs in terms of turnover and sales are mainly high-volume manufacturers like Toyota, Volkswagen and General Motors. They are part of a group of around 20 OEMs worldwide (each with several car brands) that obtain the biggest share of the market in terms of automobiles sold and achieved turnover. While the OEM side therefore shows oligopolistic structures, a polypolistic structure is observable on the supplier side [7]. The supply industry is characterized by many small to medium-sized firms that act rather locally. Depending on the position within the supply pyramid, suppliers are classified into the categories tier one, tier two and so on. Far fewer suppliers exist that have a global focus, e.g. Continental, Bosch and Denso [62]. Since these firms undertake the assembly of whole modules for the car they are often referred to as tier 0.5 suppliers.

Within the automotive industry, powertrain technologies characterize the heart of the automobile and its central purpose to fulfill mobility. Thus, for OEMs the development of powertrain systems is a crucial aspect for the creation and maintenance of competitive advantage. In the course of mass production at the beginning of the 20th century, the fossil fuel powered ICE asserted itself against other propulsion concepts. Steam-engine-based and electrical propulsion systems were banned to niche domains [43]. Nowadays, against the background of a rising environmental awareness, the scarcity of fossil fuels and political regulation and subsidies (e.g. carbon dioxide regulations or financial support of R&D), development focuses on new concepts like hybrid, battery or fuel-cell electric vehicles. However, the introduction of these technologies led to a significant increase in research activity into the conventional ICE, which today is still the dominant design (Sailing Ship Effect) [39], [47], [49], [80]. Concerning alternative powertrain technologies, there is no clear indication of which technology will be predominant in the long run. Thus, uncertainty regarding the implementation of a particular technology in the future exists and the OEMs are forced to be present in these multiple domains. Despite political and economic efforts for a change towards alternative powertrain technologies, these technologies are not yet to be considered competitive due to technical maturity and for financial and infrastructural reasons [43].

C. Collaborations within the Automotive Industry

The most frequently used criteria to analyze collaboration networks is the classification of the partners´ position in the value chain regarding a horizontal, vertical or lateral direction of collaboration [5], [56]. A horizontal network exists when the participating firms are part of the same industry and are on the same level of the value chain. In vertical networks, collaborating firms are in the same industry but on different value chain levels. Lateral networks need to be differentiated from these kinds of networks. Here the firms are neither part of the same industry nor on the same value chain level [31], [59].

In comparison to other sectors, the automotive industry is in a pioneering role regarding the creation of network structures [72]. Here, collaboration often takes place vertically along the value chain, beginning from supplier up to OEM level. Within the networks, the OEM is often in the most powerful and influential position, caused by the network's monocentric interconnections. Network theory would therefore characterize it as a focal firm [12], [44]. As such, it is responsible for controlling the network. It decides about the inclusion of new partners and the coordination and utilization of the network's resources and capabilities [41]. In contrast, other polycentric innovation networks exist where the firms involved are loosely coupled and widely independent in their network activities. Due to their powerful position, OEMs are mostly at the center of automotive networks [30], [34].

Besides vertical collaboration, a number of horizontal collaborations can be seen. OEMs collaborate increasingly in the development of new powertrain technologies [37], [68]. The joint development of technological innovations between suppliers is less common, thus there has been little attention by scientific literature to the analysis of strategic networks between these firms [78]. Considering these facts, horizontal collaborations seem to be more uncommon than vertical collaborations.

Due to rapid technological development and an increasing degree of complexity, it is more and more challenging for individual firms to remain long-term competitive [74]. This dynamic environment requires a continuous adjustment of organizational structures and the consideration of R&D collaborations [1], [38]. The increasing importance of inter-organizational collaboration in the automotive industry becomes apparent by considering the shortening development cycle of new models and technologies. As a consequence, in the sense of the relational view, the need to access external and complementary resources arises since short-term and independent development of competences and capabilities is difficult.

The simultaneous development of the established ICE technology and alternative powertrain technologies leads to uncertainties within the industry, as it is unclear which technology will prevail [43]. It can be assumed that sustainable technologies will dominate in the long run due to the limitation of resources and the implementation of further environmental regulations. Investments and the creation of specific knowledge are essential to avoid market displacement or to bring an own technology into a dominant position. In this context, sharing risks between multiple partners can be seen as an important motive for collaborative behavior [1].

III. METHODOLOGY

A. Data collection

A common method to measure the inventive activity of firms is the analysis of patent data [13], [64], [66]. This approach has several advantages mainly due to the availability of the data [2]. First, patent data allows one to analyze longitudinal development over several years [6]. Second, those firms that issue patents in the automotive industry but are usually not in the scope of research are determined. Third, innovations in a similar technological field, in our case ICE, HEV, BEV and FCEV, can be differentiated by an appropriate search strategy [23].

We used Thomson Reuters' database Derwent Innovation Index (DII) (consisting of Derwent World Patent Index and Derwent Patents Citations Index) for patent data extraction [9]. Through the combination of these indices the database provides improved information content and is more suited for the execution of a directed patent search than other patent databases like PATSTAT, by the European Patent Office. Major reasons for this advantage are the consolidation of the firms' different assignee names and their assignment to unique assignee codes [60]. The DII is a web-based database that documents over 14 million inventions or patents from over 40 patent offices, starting in the year 1963. It thereby covers both international (e.g. European Patent Office, World Intellectual Property Organization) and important national (e.g. Germany, Japan and the US) patent offices [75].

To ensure a valid dataset regarding the different powertrain technologies, we used an elaborate search strategy. In the literature, either technological classifications [2], [35], [45], relevant keywords [53], [77] or a combination of both [13], [42], [79] are used. In order to identify those patents in each technology that are assigned in networks between firms in the automotive industry, we applied a combined search strategy of classifications and keywords [47]. Table 1 shows the search queries used.

TABLE 1. SEARCH QUERIES FOR EACH TECHNOLOGICAL FIELD

Technological field	**Search query**
ICE-related patents	TS=(((internal AND combustion AND engine) OR ("IC engine")) AND vehicle*) AND TI=(vehicle* OR car*) NOT TS=((battery AND electric) OR hybrid OR "fuel cell*")
HEV-related patents	DC=(X21 AND X22) AND TI=(vehicle* OR car*) AND TS=("hybrid electric vehicle*" OR "hybrid vehicle*") NOT TS=(internal combustion engine* OR "battery electric vehicle*" OR "fuel cell*")
BEV-related patents	DC=(X16 AND X21) AND TI=(vehicle* OR car*) AND TS=("electric vehicle*" AND battery) NOT TS=(internal AND combustion AND engine* OR "fuel cell*" OR hybrid)
FCEV-related patents	DC=(X21 AND X16) AND TS=("fuel cell*" AND vehicle*) AND TI=(vehicle* OR car) NOT TS=(internal combustion engine* OR "battery electric vehicle*" OR hybrid*)

We acquired data for the timespan from 1990 to 2012. The year 1990 was chosen as the starting point because before that year almost no developments in alternative powertrain technologies are observable. The publication of a patent usually takes 18 to 24 months after an application has been made to the patent office, therefore not all patent data from 2013 to 2016 is available [47]. As the result of the data selection, we collected a total of 70,938 patents.

B. Data processing

Since patents can be assigned by firms as well as private persons and this examination is focuses on the organizational level of firms, the dataset was reduced by the removal of the irrelevant patents assigned by private persons. Due to a wide range of different firms, varying from very small to very large, a selection of assignees took place as follows.

In order to analyze the main players within the automotive industry, the top 20 OEMs and the top 100 suppliers (both according to turnover in 2014) are chosen. To avoid a categorical exclusion of automotive suppliers with a smaller turnover, we additionally select the top 30 firms with the greatest number of patent applications in each of the particular technological fields during the period under examination. With these adjustments, it is guaranteed that the dataset contains all relevant information and assignees and allows a clear presentation and interpretation of the findings.

In the next step, the assignee codes are associated with the selected firms [75]. Although the DII already provides a certain consideration of different assignee names, a manual assignment takes place in order to consider relationships between firms regarding majority shareholding or subsidiaries. This is especially important for larger groups of firms like the Volkswagen Group [50], [55].

All patents from firms that are not part of the previous selection (top 20 OEMs, top 100 suppliers, top patent holders) are excluded from the dataset. As a result, 54,553 patents remain in the dataset. In the last step for selection, all patents are excluded that are assigned by only one of the considered firms and are therefore no result of innovative collaboration. This reduces the dataset to 1,912 patents with at least two relevant assignees for the examination of network-like relations.

In the following the validity of the procedure is checked. The validity shows if the predetermined construct can be applied in order to make reliable statements about the issue under examination. Due to a negative delimitation within the search query used, the search strategy already provides an objective and reliable result. Nevertheless, a patent might not have an actual application within one of the powertrain technologies. Thus, a manual validation process is conducted on the 1,912 patents. The validation shows that 96% of the patents are categorized correctly to the particular technologies (see Table 2). Therefore, a highly valid dataset exists.

TABLE 2. RESULTS OF THE VALIDATION PROCESS

	ICE	HEV	FCEV	BEV	Total
Number of Patents	768	648	340	156	*1,912*
with respect to propulsion technology	737	607	335	152	*1,831*
without respect to propulsion technology	31	41	5	4	*81*
Share of valid Patents	96.0%	93.7%	98.5%	97.4%	*95.8%*
Share of non-valid Patents	4.0%	6.3%	1.5%	2.6%	*4.2%*
Total	*100.0%*	*100.0%*	*100.0%*	*100.0%*	*100.0%*

IV. RESULTS & DISCUSSION

A. Descriptive statistics

The total number of 1,912 patents is issued by 94 different assignees (see Table 3). Eighteen of these firms are OEMs (19%) and 76 firms are suppliers (81%). Only a few patents are held by three or four assignees. This shows the high tendency of firms in the automotive industry to form a bilateral collaboration. Sixty percent of all patents in the sample belong to alternative powertrain technologies, whereof hybrid technology (34%) has the main share.

To further analyze the collaboration between participating firms, trilateral and quadrilateral relationships are separated into bilateral relationships. For example, a single patent with three assignees (A, B, C) is subdivided into three bilateral connections (A-B, A-C, B-C). As a result, 2,025 collaborations are analyzed. Figure 1 shows the yearly patent applications based on all collaborations in each of the four technological areas.

TABLE 3. SAMPLE STATISTICS

	N	%
Total Number of Assignees	94	100.00
OEM	18	19.15
Suppliers	76	80.85
Total Number of Patents	1,912	100.00
Number of Patents shared by		
two assignees	1,869	97.75
three assignees	34	1.78
four assignees	9	0.47
Powertrain Technology		
ICE	768	40.17
HEV	648	33.89
FCEV	340	17.78
BEV	156	8.16

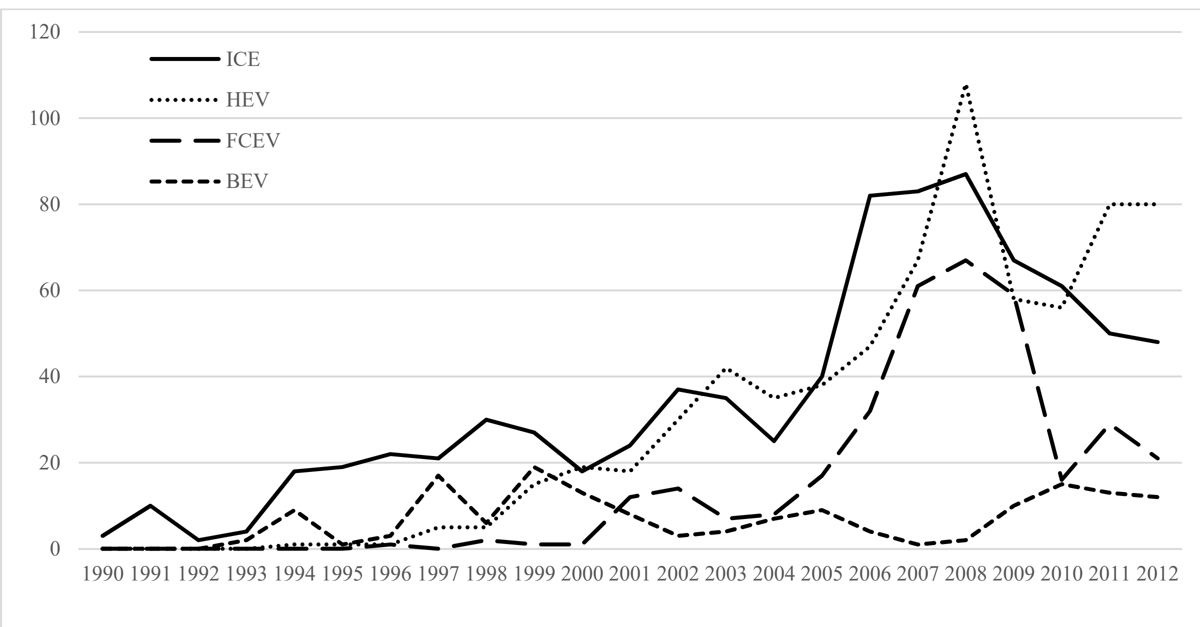

Figure 1. Yearly joint patent applications

TABLE 4. MAIN PARTNERSHIPS SUBJECT TO DIRECTION OF COLLABORATION AND TECHNOLOGICAL FIELDS

Bilateral cooperation		Main partnerships	Technological fields
Vertical 1590 (78.5%)	OEM/Suppliers 1590 (100.0%)	37.2% Toyota/Denso	62.1% ICE; 23.9% HEV; 12.2% FCEV; 1.9% BEV
		23.1% Toyota/Aisin	54.2% HEV; 29.2% FCEV; 15.5% ICE; 1.1% BEV
		6.8% Toyota/Toyota Boshoku	43.5% ICE; 28.7% HEV; 17.6% FCEV; 10.2% BEV
		4.1% Toyota/Panasonic	52.3% BEV; 47.7% HEV
Horizontal 435 (21.5%)	OEM/OEM 243 (55.9%)	36.2% Daimler/Ford	100.0% FCEV
		17.1% Daimler/Mitsubishi	58.1% HEV; 41.9% ICE
		5.3% Daimler/BMW Group	53.8% ICE; 46.2% HEV
		5.3% Daimler/Fiat Chrysler	69.2% HEV; 15.4% ICE; 15.4% BEV
	Suppliers/Suppliers 192 (44.1%)	39.1% Samsung/Bosch	64.0% HEV; 36.0% BEV
		6.8% Hitachi/Shin Kobe Electric Machinery	61.5% HEV; 30.8% BEV; 7.7% ICE
		6.3% Bosch/Continental	100.0% ICE
		5.2% Aisin/Denso	60.0% HEV; 30.0% ICE; 10.0% FCEV

B. Direction of collaboration

The direction of collaboration is either vertical (OEM/supplier) or horizontal (OEM/OEM or supplier/supplier). No lateral collaborations exist, since all firms are from the automotive industry.

Table 4 shows that almost 80% of all collaborative patent applications considered result from vertical collaborations between OEMs and suppliers. It is important to emphasize that within this group, Toyota is a participant in all of the four largest partnerships. However, these partnerships differ in relationship intensity and in the technologies to which the patents applied. While Toyota's collaboration with Denso as well as Toyota Boshuko created innovations mainly in the fields of ICE and HEV technology, the collaboration between Toyota and Aisin was predominantly in the fields of HEV and FCEV technology. The partnership with Panasonic is exclusively focused on the joint development of BEV and HEV technology. In detail, this collaboration's objective is developing the core components of electronic powertrain technology, namely batteries. Panasonic already has been producing for Toyota (e.g. for the plug-in hybrid model of the Toyota Prius) [54]. From Toyota's perspective, the main reason for this kind of collaboration is based on its partner's know-how in particular technology fields. While a pure merger can endanger sustainable competitive advantages due to an insufficient development of internal competencies, an OEM is able to create the necessary knowledge and core competencies through a collaboration with appropriately equipped suppliers [73]. This incorporates an important strategic aspect, especially in a competition between rival technologies with uncertain consequences [33].

While most collaboration takes place along the value chain, one fifth of partnerships occur on a horizontal level (Table 4). The share of collaborations between OEMs (55.9%) is slightly higher than the share of collaborations between suppliers (44.1%). It seems surprising that a number of collaborations between OEMs exist. But the dynamic progress of interconnected forms of collaborative work, together with changing customer requirements in the last two decades, makes partnerships desirable. As the creation of own competencies usually implies high resource requirements, collaboration between competing OEMs becomes more frequent [8], [37].

The results show that the **automotive manufacturer** Daimler is the most collaborative OEM in terms of horizontal collaboration. Daimler's partnership with Ford is especially strong. Here, the development of innovative fuel cells – and with this an acceleration of pure electric drive – is reached by a concentration on the specific competences of both firms. The collaboration is formed out of a 10-year alliance of Daimler, Ford and Ballard Power Systems that lasted until 2007. Ballard Power Systems is a pioneer in the development of fuel cells. In 2008, Daimler and Ford jointly bought Ballard Power Systems and founded the joint venture Automotive Fuel Cell Cooperation [16]. The joint venture´s goal is to push fuel cell technology to reach a point that allows a cost-covering mass production and by this ultimately spread the technology [4]. The high ambitions of the firm and the importance of the horizontal collaboration is underpinned by the fact that, as a consequence of the joint venture, Renault-Nissan was included in the common commercialization of the fuel cell in 2013 [17]. Although Daimler`s activities are aimed at an emission-free technology in the long run, other partnerships point to the fact that Daimler is not focusing exclusively on the development of alternative concepts. The partnerships with Mitsubishi or the BMW Group show that Daimler still focuses on new innovations in the domain of conventional powertrain technologies.

The most collaborative patent applications **on the supplier level** concern the development of BEV and HEV technology and are between Bosch and Samsung. The high fraction of collaborative patents is a result of the 2008 commonly founded joint venture SB LiMotive that is focused on battery cells and battery systems for electronic drive technologies. Through the union of the competencies of Samsung in lithium-ion technology and Bosch in the automotive sector, SB LiMotive is aiming for a leading position in the market for lithium batteries for BEV and HEV [10]. However, due to contractual regulation limiting the access of know-how beyond the collaboration, and a changing dynamic in the market, the collaboration was ended after four years [36]. In total, the results indicate that the collaboration of competitors at both the OEM and the supplier level can generate a competitive advantage within network-like partnerships, especially regarding access to strategic resources and knowledge.

The central position of the OEMs can be seen in Figure 2. The OEMs (grey circles) are mostly integrated in central positions and have multiple links, while numerous suppliers (white circles) have few or just one collaborative partner for common patent applications and are accordingly positioned at the outside ends of the network structure. The size of the respective circles represents the number of different partners a firm has within the automotive industry. Furthermore, the number of collaborations and patents show different strategies. While some OEMs seem to have core partners within the network (such as Toyota has with Denso and Aisin; and Daimler with Ford), other subnetworks emerge without this concentration of patents (such as Honda or Renault-Nissan).

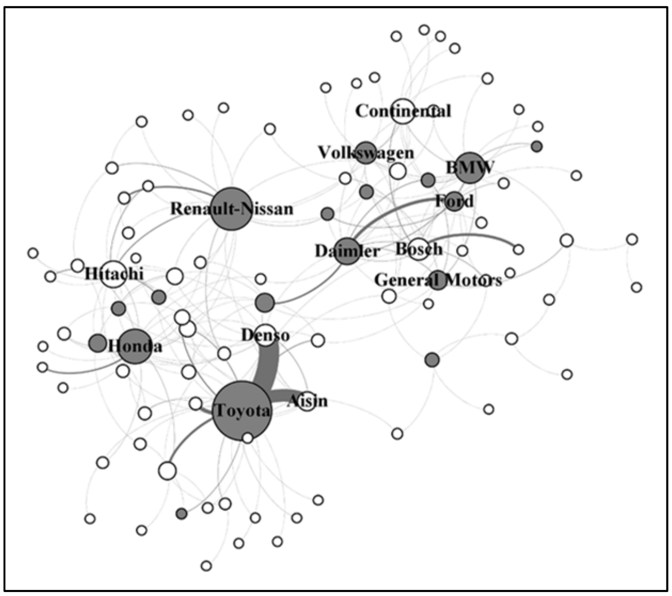

Figure 2. Graphical representation of the network structure

Another aspect in a similar context is the existence of different kinds of linkages: direct and indirect ones. Toyota, with its central position in the network, shows a high number of direct linkages to other firms. In addition, some of these actors not only collaborate with Toyota itself but also with other partners of Toyota. Other network members in turn are connected exclusively with one OEM or, indirectly, with one of the OEMs partner.

The relational view reflects the importance of direct relations. Through direct access to competencies and knowledge, the collaborating firms encourage their innovation activities and with this their generation of competitive advantages [58]. Empirical examinations show that the influence of indirect linkages can have a positive impact on innovation activities of a firm as well, even if the number of direct relations moderates this impact [3]. This paper deals with collaboration that is measured by joint patent applications in a specific domain of R&D. A question arises as to whether the results of this examination are transferable to other cases of collaboration. The two examples given in the following paragraphs clarify the answer to that question.

If two suppliers are connected to one OEM at the same time but are not linked to each other then it is unlikely that either supplier would benefit from the collaboration of the other supplier with the same OEM. If the suppliers are competitors then each supplier will prevent sensitive know-how from passing to the competitor through the OEM. Moreover, each supplier will try to enhance its own business relationship with the OEM and will aim at achieving an exclusive collaboration. The second example is based on collaboration between suppliers in the case where just one supplier has a direct relation to a particular OEM. The advantageousness of this network can be explained from multiple perspectives. The OEM reduces the number of its collaborating partners with beneficial effects regarding coordination costs while maintaining the same level of innovativeness. Therefore, there is a transition on supplier level from the development of single components towards the development of comprehensive solutions of modules and systems [37]. Additionally, the OEM benefits from an increase of its supplier's innovativeness through the alignment of the supplier´s and its collaborating supplier´s individual core competencies. The indirectly linked supplier can achieve an advantage mainly through the fact that, without the underlying assignment between the OEM and the common partner, no business relationship per se would exist.

At last, the specific structure of the automotive industry becomes apparent. While the OEMs dominate the innovative efforts of most suppliers, some big suppliers (Tier 0.5) have emerged and seem even to have increased in importance. On the other hand, most suppliers are clearly dominated by OEMs and a few big suppliers. These focal firms tend to collaborate with many different firms that have different core competencies. Therefore, OEMs and big suppliers do not need to develop every innovation on their own – and can drop certain suppliers if further improvements seem unlikely.

C. *Technological Change*

The number of patents applied for jointly by two or more firms has clearly increased in the period between 1990 and 2012. Besides ICE technology, an enormous increase of patent applications can be seen in HEV and FCEV technology. This raises different questions: Do firms need new knowledge to develop alternative powertrain technologies? Would firms rather use vertical or horizontal collaboration in order to be innovative? To answer these questions, Figure 3 illustrates the number of patents that can be imputed to either horizontal or vertical collaborations each year, split between alternative and ICE patents. The diagram gives some key insights into the nature of collaborations when technologies emerge. We discuss these in the following paragraphs.

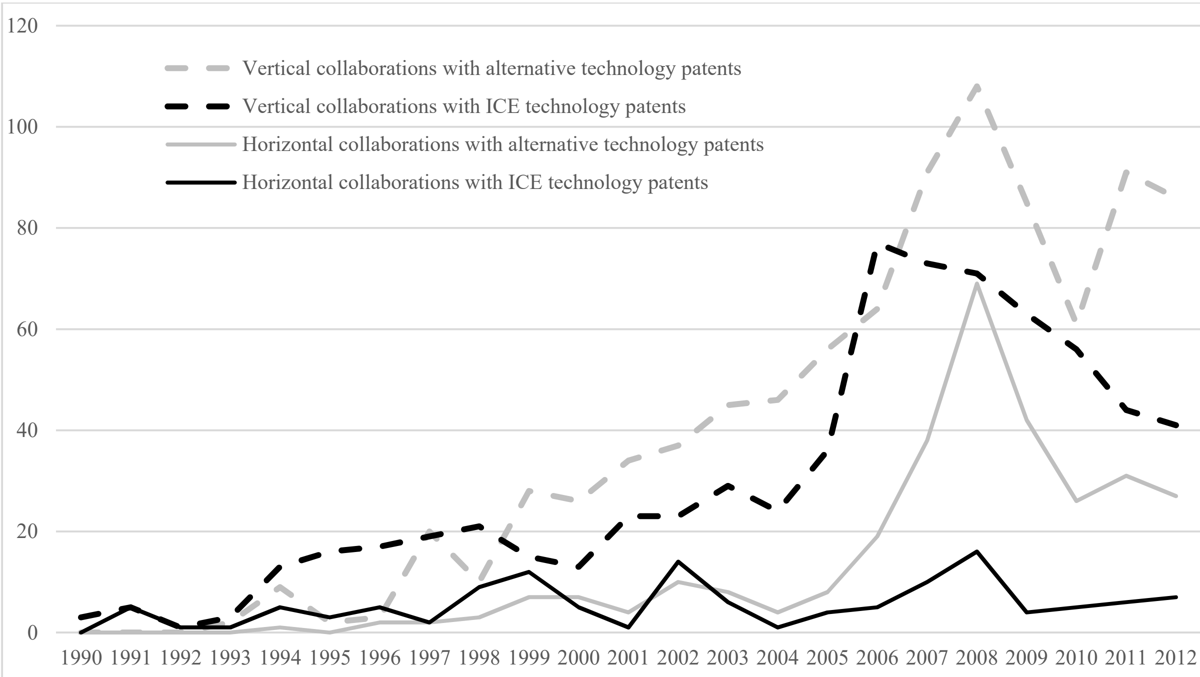

Figure 3. Horizontal and vertical collaborations for each powertrain technology

Two major trends become obvious in Figure 3. The first is a strong increase of joint patent applications since the year 2005, with its peak in 2008. The start of the automotive crisis in this year led to fewer patent applications in the following years. Since the reduction in numbers of applications cannot be seen in patent studies with a non-network focus [35], the decreasing numbers in this sample show that the automotive crisis had a considerable impact on joint innovation activities. Second, the total number of patent applications in the three alternative powertrain technologies are higher than the number of applications in the ICE technology. While the ICE technology was still dominant in the first years of the period, in every year since 1999 the joint patent applications in the alternative technologies outnumber those in the ICE technology.

The relational view provides explanatory approaches for these developments. Research and development in the area of new powertrain technologies is associated with high risks and costs. The combination of knowledge and resources from different partners can lower these risks. The higher number of patents issued shows that the partners have institutionalized their collaboration and use knowledge-sharing routines. According to the theory, this allows the generation of relational rents that a single firm would not be able to achieve on its own.

Figure 3 also gives insights into the direction of collaboration over time. Patents from vertical collaborations have increased strongly since 2000. This is true for both alternative and ICE technology. This development shows a common trend in the automotive industry. The OEMs draw on the innovative activity of suppliers. That is, suppliers innovate in certain technologies, expecting to be able to sell this technology to one or several OEMs. Therefore the risks and costs, especially for the alternative technologies with an uncertain future, are transferred from the OEM to the suppliers. In the end, the suppliers that will benefit are those that are able to deliver the components for the required technology.

Patents from horizontal collaborations are fewer in number than those from vertical collaborations. ICE technology patents, especially, are uniformly few over the whole period under consideration. In contrast, horizontal collaborations in alternative technologies have increased strongly since 2006. Besides collaborating with suppliers, OEMs have increasingly collaborated with other OEMs during that time. Collaboration between suppliers also increased. The intensified relationships on this level also serve to minimize risks.

The results presented give a clear picture of the nature of collaboration in the field of powertrain technologies within the automotive industry. Vertical collaborations increase in general, i.e. for conventional as well as alternative powertrain technologies; whereas horizontal collaborations increase due to technological change. The former is not a surprising development, as patent applications in the automotive industry have increased in number in the last decades [2]. Due to the strong hierarchic structure of the industry, more patent applications lead to more collaborative patents between OEMs and suppliers. In contrast, horizontal collaborations do not increase significantly for the ICE, but increase significantly for alternative powertrain technologies. This clearly shows that the huge challenge of developing low emission vehicles demands far more than just normal efforts. Suppliers as well as OEMs are therefore changing their behavior from a competitive approach to co-opetition regarding alternative powertrain technologies. Consequently, we can answer the second research question as follows: While vertical collaboration in alternative powertrain technologies is at a level that could be expected (based on the development of all technologies), technological change specifically encourages horizontal collaboration.

D. Limitations

A first limitation of the present study is the effect of the existence of multiple national patenting systems. The results for Japanese firms in particular illustrate that the number of patent applications in Japan – and so the intensity of collaboration – is often higher compared to firms from other countries. Although this affects our results, it does not change the general insights of the direction and strength of the network structure.

The total number of joint patent applications is rather small compared to the total sample of patents in powertrain technologies for cars. In addition, not every innovative activity of two firms results in joint patents. Therefore, the network structure presented is merely an extract of the existing relations between firms in the automotive industry, and their intensity. As an example, the alliance between Daimler and Renault-Nissan, started in 2010, has not led to a patent in our dataset. It was not until 2015 that these firms applied for a small number of joint patents, mainly in FCEV technology.

A third limitation relates to the value of a particular patent. Patents are indicators of the creation of technological knowledge but they do not contain information about the quality and economic value of that knowledge. For our analysis, we quantify each patent with the same value, whether or not it is economically profitable. Considering qualitative information, e.g. how often a patent has been cited, can give an indication about its importance and commercial exploitability. Hence, the quantitative analysis of innovation networks in connection with qualitative measures is an interesting future field of research [30].

V. CONCLUSION

The present paper deals with the examination of innovation networks within the automotive industry by performing a quantitative patent analysis. By investigating joint applications for patents regarding powertrain technologies by firms within the automotive industry, we discuss two different research questions. First, a detailed analysis of the direction of collaboration – either vertical or horizontal – is conducted. Second, we examine the impact on joint patenting of the technological change favoring low-emission vehicles. The findings are interlinked with the theoretical framework of the relational view. Additionally, the paper questions how the findings and the resulting knowledge can be verified by practical examples.

The results indicate a fundamental trend towards joint patent applications, which had its peak in the year 2008. Since then the number of applications has decreased until the end of the observation period. In line with the value chain, almost 80% of all collaborations are vertical, that is between OEMs and suppliers. The theoretical assumptions can be mainly confirmed and thus the question is answered positively: general aspects of the network research could be transferred to the special form of automotive innovation networks.

Regarding the technological change examined in this paper and its influence on the creation of innovation networks, it can be stated that both the general increase in the development of regenerative drive concepts and a corresponding growth of R&D collaboration can be observed. Nevertheless, it is necessary to mention that the number of collaborations regarding the ICE technology is also rising. The analysis of the network structure shows that numerous OEMs have multiple collaborating partners and are thereby positioned in central positions of the network. In addition, a multitude of indirect linkages increases the innovative input without coordination costs for the OEM.

In conclusion, collaboration is a powerful strategy to benefit from heterogeneous competencies and risk sharing, which is vital for firms on every level of the value chain. Although theory predicts competitive advantages from collaboration, the total number of joint patent applications indicate a decrease in the number of these partnerships between automotive firms. As further technological development is unpredictable, firms – especially the incumbent OEMs – should keep several partners for each technology. As we highlighted, Toyota is an excellent illustration of this. Within different collaborative relationships Toyota is successfully present in all powertrain technologies and is a pioneer in hybrid cars (Toyota Prius) and fuel cell cars (Toyota Mirai). Other OEMs can therefore learn from Toyota's collaborative strategy in order to be prepared for future technological challenges.

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APPENDIX

APPENDIX 1. LIST OF OEMS AND SUPPLIERS.

Firm	Type	Part of the sample	Firm	Type	Part of the sample	Firm	Type	Part of the sample
3M Automotive	Supplier	x	Hankook Tires	Supplier		NSK Group	Supplier	x
Aisin Seiki	Supplier	x	Harman International	Supplier		NTN	Supplier	x
Alps Electric	Supplier	x	Hella	Supplier		Panasonic	Supplier	x
American Axle	Supplier	x	Hitachi	Supplier	x	Pioneer	Supplier	x
Asahi Glass	Supplier	x	Honda	OEM	x	Pirelli	Supplier	
Aunde	Supplier		Honeywell (Allied Signal)	Supplier		Plastic Omnium	Supplier	
Autoliv	Supplier		Hutchinson	Supplier		PPG Industries	Supplier	
Behr	Supplier	x	HVCC	Supplier		PSA Peugeot Citroën	OEM	x
Benteler	Supplier		Hyundai Kia	OEM	x	Renault-Nissan	OEM	x
BMW	OEM	x	Hyundai Mobis	Supplier	x	Saint-Gobain	Supplier	x
Borg Warner	Supplier	x	IAC	Supplier		Samsung	Supplier	x
Bosch	Supplier	x	Illinois Tool Works	Supplier	x	Samvardhana Motherson Group	Supplier	
Bridgestone / Firestone	Supplier	x	Inteva	Supplier		Sanyo Electric	Supplier	x
Brose Fahrzeugteile	Supplier	x	Isuzu	OEM		Schaeffler	Supplier	x
Calsonic	Supplier	x	Jatco	Supplier	x	Shin Kobe Electric Machinery	Supplier	x
Chery Automobile	OEM		Johnson Controls	Supplier	x	Showa	Supplier	x
Continental	Supplier	x	JTEKT	Supplier	x	SKF	Supplier	x
Cooper Standard	Supplier		Keihin	Supplier	x	Sony	Supplier	x
Cooper Tire & Rubber Co.	Supplier		Knorr-Bremse	Supplier		Sumitomo Electric Industries	Supplier	x
Cummins	Supplier	x	Koito Manufacturing	Supplier		Sumitomo Riko	Supplier	
Daimler	OEM	x	Kostal	Supplier		Sumitomo Rubber Industries	Supplier	
Dana	Supplier	x	KSPG Automotive	Supplier		Suzuki	OEM	x
Delphi	Supplier	x	Lear	Supplier		Takata	Supplier	
Denso	Supplier	x	Leoni	Supplier	x	Tata	OEM	x
Dongfeng	OEM		Linamar	Supplier		TE Connectivity	Supplier	
Doosan	Supplier	x	Magna International	Supplier		Tenneco	Supplier	x
Dräxlmaier	Supplier	x	Magneti Marelli	Supplier		Tesla	OEM	
Dupont	Supplier	x	MAHLE	Supplier	x	ThyssenKrupp Automotive	Supplier	x
Eaton	Supplier	x	Mando Corp	Supplier	x	TI Automotive	Supplier	x
Eberspacher	Supplier	x	Mann + Hummel	Supplier	x	Tokai Rika	Supplier	x
Faurecia	Supplier	x	Martinrea International Inc	Supplier		Toshiba	Supplier	x
Federal Mogul	Supplier	x	Maxell	Supplier	x	Toyo Tire & Rubber	Supplier	x
Fiat Chrysler	OEM	x	Mazda	OEM	x	Toyoda Gosei	Supplier	x
Flex-N-Gate	Supplier		Meritor	Supplier		Toyota	OEM	x
Ford	OEM	x	Michelin	Supplier		Toyota Boshoku	Supplier	x
Freudenberg	Supplier	x	Mitsuba Corp	Supplier	x	Toyota Industries Corporation	Supplier	
Fuji Eletectric	Supplier	x	Mitsubishi	OEM	x	TRW	Supplier	
Fuji Heavy Industries (Subaru)	OEM	x	Mitsubishi Chemical	Supplier	x	TS Tech	Supplier	
Futaba Industrial	Supplier	x	Mitsubishi Electric	Supplier	x	Valeo	Supplier	x
Geely (Volvo)	OEM	x	Mitsubishi Heavy Industries	Supplier	x	Visteon	Supplier	x
General Electric	Supplier	x	Mitsubishi Materials	Supplier	x	Volkswagen	OEM	x
General Motors	OEM	x	NEC	Supplier	x	Wabco	Supplier	
Gestamp	Supplier		Nemak	Supplier		Webasto	Supplier	
Getrag	Supplier	x	Nexteer Automotive	Supplier		Weichai Power	Supplier	
GKN	Supplier		NGK Insulator	Supplier	x	Yamaha Motor	Supplier	x
Goodyear tire and rubber	Supplier		NGK Spark Plug	Supplier	x	Yazaki	Supplier	x
Grupo Antolin	Supplier		NHK Spring	Supplier	x	Yokohama Rubber	Supplier	
GS YUASA	Supplier	x	Nippon Sheet Glas	Supplier	x	ZF Friedrichshafen	Supplier	x