Università
Ca'Foscari
Venezia

Department
of Management

Working Paper Series

Alessandra Perri, Daniela Silvestri and Francesco Zirpoli

Change and stability in the automotive industry: a patent analysis

Working Paper n. 5/2020
September 2020

ISSN: 2239-2734

Change and stability in the automotive industry: a patent analysis[1]

ALESSANDRA PERRI
alessandra.perri@unive.it
Dept. of Management
University of Venice

DANIELA SILVESTRI
daniela.silvestri@unive.it
Dept. of Management
University of Venice

FRANCESCO ZIRPOLI
fzirpoli@unive.it
Dept. of Management
University of Venice

(October 2020)

Abstract. This study[2] explores the evolution of the knowledge base of the dominant Original Equipment Manufacturers (OEMs) in the global automotive industry. Using data on patent families, we reconstruct and analyze their innovative portfolio in the period 1990-2014. The analysis documents experimentation in new technical fields as well as stability in industry-specific technical areas, allowing to draw implications on the underlying industry dynamics. Specifically, our results show that despite the emergence of technological opportunities in new and once-unrelated technical domains, the importance of core automotive technologies has increased over the period of analysis. At the same time, the relative position of carmakers along different performance dimensions has remained quite stable, suggesting that the technological capabilities that have traditionally driven success in this industry continue to play a key role in explaining firms' competitive strength.

Keywords: knowledge base evolution, automotive industry, patent analysis.

JEL Classification Numbers: L62, O34.

Correspondence to:

Daniela Silvestri: Dept. of Management, Università Ca' Foscari Venezia
San Giobbe, Cannaregio 873
30201 Venezia, Italy

E-mail: daniela.silvestri@unive.it

[1] We are grateful to the European Patent Office Academic Research Programme Grant 2018 for funding this research.

[2] This working paper has been submitted for consideration to the Oxford Handbook of Industry Dynamics. Please cite it as: Perri A., Silvestri D., & Zirpoli F. (forthcoming), Change and Stability in the Automotive Industry: A Patent Analysis, in Kipping M., Kurosawa T., Westney, E. (eds) Oxford Handbook of Industry Dynamics, Oxford University Press.

1. Introduction

The role of technology evolution as a driver of industry development has been central to innovation and competition studies. Prior literature building on the Schumpeterian tradition and on the evolutionary theory of change (Nelson and Winter, 1982) has highlighted the strong connection linking an industry knowledge base and industrial dynamics. Thus, understanding the industrial dynamics of technological competition requires an accurate analysis of the knowledge base of the industry and of the resulting patterns of innovative activities (Malerba and Orsenigo, 1996).

For several decades, scholars working in the field of technology and innovation management have adopted the automotive industry as an ideal empirical setting to investigate key firm-level and industry-level phenomena, including the new product development process or the orchestration of vertical networks of innovation (Clark, et al.,1987; Takeishi and Fujimoto, 2003; Zirpoli and Becker, 2003). Nonetheless, with the exception of Klepper (2002), who explored the early faces of the automotive industry, no further analysis has accurately documented the patterns of industrial innovation and technological development in this setting. As a consequence, a comprehensive and dynamic mapping of the knowledge base of the largest manufacturing industry in the world is still missing.

This study seeks to fill this gap by exploring the evolution of the knowledge base of the automotive industry, drawing implications into how it has affected the industry's structure in terms of triggering shakeouts and/or altering the competitive position of the industry dominant players. In doing so, it addresses a long-standing debate on the role of change and stability in the industry's knowledge generation. Previous literature has suggested that the automotive industry is simultaneously exposed to "*drivers of change and sources of stability*" (Schultze et al., 2015; 605), which are expected to reflect in the industry's knowledge base. Yet, no systematic evidence exists in support of this statement, possibly due to the complexity of mapping the knowledge base of a complex-product industry. We carry out this challenging undertaking and corroborate the idea that both change and stability have characterized carmakers' knowledge generation over the 25-year period analyzed in this study (1990-2014).

The evolution of the knowledge base of the automotive industry deserves attention for a number of reasons. First, this context has a major impact on the economy. As an example, the number of employees in the "Motor vehicles, trailers, semi-trailers" manufacturing sector worldwide has been estimated at nearly 14 millions workers (UNIDO, 2019), and the average annual turnover of the world automobile industry is more than 2.75 trillions Euro corresponding to 3.65% of world Gross Domestic Product (GDP)[3]. Second, public policy has been systematically intervening on its patterns of innovative activities in the attempt to cope with the externalities that the industry produces (notably pollution), but great debate exists on the effectiveness of such policies. Finally, the industry is characterized by an exceptional degree of complexity (Maxton and Wormald, 2004; Womack et al., 1990, Jacobides et al., 2016) involving product architectures, organizational processes, and task partitioning. Thus, investigating the evolution of its technological competences may help shedding light on the "ambiguous and dynamic" relationships linking the automotive industry's knowledge base to its product and organizational architecture (Zirpoli and Camuffo, 2009).

Empirically, we reconstruct and analyze the patent portfolios of the top 25 original equipment manufacturers (OEMs) over a 25-year period (1990-2014). We use the Orbit patent database that, contrary to public patent data sources, provides advanced tools to accurately trace the evolution of firms' technological knowledge. Consistent with observable market and institutional trends that are shaping the industry's evolution (namely, electrification and digitalization), we find that technologies that originally occupied only a marginal position in the knowledge base of the industry (e.g., conversion of chemical into electrical energy, electric digital data processing and recognition) have gained notable importance especially in the last 10 to 15 years of our analysis. At the same time, the core automotive technologies that have traditionally characterized mass-produced vehicles (e.g., vehicles' parts, conjoint control of vehicle subunits) have not only remained central in the industry's knowledge base, but have also increased their relative weight in the industry's overall knowledge production. Overall, our findings uncover a systematic co-existence of technological stability and change that, interpreted in combination with key facts of the industry's evolution, provides insights into the determinants of the current competitive dynamics that characterize this context.

The chapter is organized as follows. First, we highlight the link between the knowledge base leading to patenting and the industry dynamics. Then, we describe the main characteristics of the automotive setting in relation to the industry's structure and trends. Along this line we also present the data and methodology used. Finally, we describe the results by documenting how the knowledge base of the industry has evolved over time, offering insights into the relationship between the technological and competitive dynamics of the industry.

---

[3]Saberi, B. (2018). The role of the automobile industry in the economy of developed countries. *International Robotics & Automation Journal*, *4*(3), 179-180.

2. Industry dynamics and the evolution of the knowledge base

An industry's dynamics of technological competition are strongly linked to the evolution of the industry's knowledge base. Innovation processes are highly heterogeneous across sectors (Pavitt, 1984; Malerba, 2002), and such heterogeneity contributes to determine the structure of the industry, its organizational practices and institutional arrangements. To stay abreast of technological discontinuities, firms in an industry typically need to perform a significant amount of upfront research in order to assess the feasibility of new technological solutions or standards. Therefore, firms' innovation activities may change over time in response to potential technological shifts calling for phases of explorative innovation aimed at generating knowledge in new domains.

Research into the evolution of an industry's knowledge base as resulting from firms' upstream research has mainly focused on sectors characterized by a tight association between the *bodies of knowledge* and the *bodies of practices*, i.e., science-based industries (Pavitt, 1998). Conversely, in industries where such association is less visible, such as the automotive industry, scholars working in the field of technology and innovation management have mainly focused on the dynamics of complex downstream development activities (Clark and Fujimoto, 1991). As a consequence, we still have a limited understanding of how the knowledge base of a complex product industry influences the evolution of this industry's dynamics along different dimensions, such as the industry's sources of information, problem solving procedures, competition and vertical interactions.

The outcomes of an industry's upfront research efforts can be traced through the analysis of this industry's patenting activity. For a patent to be granted, the invention must be novel, non-trivial, and useful (Schoenmakers and Duysters, 2010). Thus, patents are used in the innovation studies as a measure of new knowledge development. Analyzing the knowledge protected in patent documents enables to map the evolution of the technological competences that firms have accumulated over time.

In the automotive industry, OEMs make an intense use of patents and devote a significant amount of resources to maintain and renew their patent portfolios (Cohen et al., 2000). This happens despite the fact that patents tend to be largely ineffective as protection tools in many of the technological fields that are relevant to develop a car (e.g., electronics). Firms often patent for strategic reasons (Hall and Ziedonis, 2001) or to signal their investment in specific technological domains. Specifically, the complexity of the car, a multi-technology product with interconnected components and subsystems, is likely to encourage OEMs to use patents to manage the wide networks of suppliers and external collaborators in an attempt to maintain their own competitive advantage and ensure their freedom to operate (Trombini and Zirpoli, 2013). Thus, patent data serve as a good indicator of the inventive activity of companies operating in the automotive industry (Aghion et al., 2016).

Prior studies using patents to trace knowledge development in the automotive industry have mainly focused on the evolution of very specific phenomena or technologies without providing an overall picture of the knowledge base of the industry. As an example, literature has looked at patent data to analyze trends in the electrical vehicles production (De Mello et al., 2013), battery value chain reconfiguration (Huth et al., 2013; Golembiewski et al., 2015), energy storage solutions (Flamand, 2016) and the role of environmental policy regulations in the cross-border flow of compliance-related technologies (Dechezleprêtre et al., 2015), to name a few. In a departure from this approach, our study leverages patent data with the aim of offering a dynamic account of the industry's overall knowledge base.

3. The global automotive industry

The automotive industry is a unique environment where complexity permeates product architectures, technology, organizational processes, as well as design and engineering activities. Vehicles are in fact integral products (MacDuffie, 2013) that result from the combination of a large number of components, incorporating different technologies linked to each other by complex interdependences (Zirpoli and Becker, 2011) and spanning from mechanics, to electronics, telematics and software. Just as an example, modern electric cars might comprise more than 10 million lines of computer code (Branstetter et al., 2019) and up to 150 programmable computing elements (O'Donnell, 2017).

Historically, the limited group of OEMs that survived the massive consolidation following the emergence of the dominant design in 1920s have maintained leading positions in the industry by strengthening their system-integration capabilities, protected from the entry of new players by significant economies of scale (MacDuffie and Fujimoto, 2010; Schultze et al., 2015). For several decades, their market dominance enabled them to accumulate massive competences in manufacturing, design and supply chain management, while the product architecture remained substantially stable despite significant component innovation (MacDuffie and Fujimoto, 2010; Schultze et al., 2015).

Although the incumbents' legacy in terms of capabilities has been identified as an important source of *stability* in the automotive industry (Schultze et al., 2015), previous literature also suggests that the emergence of new technological trajectories has traditionally characterized this context, whose knowledge base has been in constant evolution (Maxton and Wormald, 2004) as a way to respond to pressures arising from complex governmental regulations, increasing globalization and technological advances that have gradually gained important roles in product design (Schultze et al., 2015). As an example, it has been documented that, since its early stages, the industry has been leading the adoption of robotic and automation processes with substantial use of information and communication technologies in product development and supply chain management (Womack et al., 1990). Similarly, in more recent years, it embraced the use of electronics and internet technology, which stepped into both vehicle design and business model innovation (Schultze et al., 2015).

The abovementioned drivers of *change* prompted a compelling need to source knowledge from different, once-unrelated fields. This has driven OEMs to promote a "distributed innovation" model, where innovation arises from the joint contribution of a network of actors endowed with complementary specialized knowledge and operating at different stages of the value chain (Fine, 1998; Zirpoli and Becker, 2011; Jacobides et al., 2016). Thus, the industry is typically organized in a pyramidal structure, where OEMs coordinate a network of suppliers and sub-suppliers (Whitford, 2005) that influences the type of knowledge OEMs may access. OEMs acting as system integrators collaborate with several subcontractors and suppliers which are no longer specialized in the mere provision of components but directly involved in the generation of new technical knowledge (Antonelli and Calderini, 2008; Magnusson and Berggren, 2011; Borgstedt et al., 2017).

The growing complexity of product development and the division of innovative labor have come along with increasing sophistication of design and engineering tools, such as virtual development, simulation techniques (Becker and Zirpoli, 2005), and digital technologies (Lee and Berente, 2012). As a result of the ongoing technology evolution, problem solving and innovation processes have also changed substantially. More generally, there is a common belief that automotive digitalization and electrification will ultimately generate disruptive outcomes such as autonomous driving and "mobility as a service" (MaaS) and that, accordingly, OEMs will be required to master a changing and expanding range of technological fields. As an example, the production and assembly of the battery module into electrical vehicles require mechanical, electrical and chemical competences with a series of challenges linked to testing, validation and final incorporation of the battery component into the vehicle (Huth et al., 2013).

In order to add a systematic analysis to the anecdotal evidence pointing toward the co-existence of stability and change in the technological competencies of the automotive industry, the remainder of the chapter systematically documents how its knowledge base has evolved over time. More specifically, we seek to provide solid and comprehensive evidence that illustrates how the industry has been balancing the focus on its core automotive technologies with the experimentation and development of competencies into more distant domains for potential future deployment. In so doing, we also aim at offering insights into the relationship between the technological and competitive dynamics of this context.

4. Empirical strategy

4.1 Data collection and methodological approach

We focus our investigation on OEMs' patent portfolio. This decision was premised on two considerations. First, OEMs have traditionally hold both architectural and component specific knowledge (Takeishi, 2002) that in turn have secured them the role of system integrator *vis a vis* other players, such as first tier suppliers, in the automotive value chain (Jacobides et al., 2016). This is also due to the fact that automotive OEMs diversify much less their product portfolio than their first and second tier suppliers. This prominent position of OEMs in the industry still holds in the face of recent industry developments. OEMs, in fact, appear to maintain their role as system integrator also after the introduction of new technologies, as the electric power trains and batteries, by combining new and old technologies into vehicle design (Rong et al. 2017). Second, from a demand side vantage point, OEMs' role as system integrators bear legal and regulatory responsibility towards customers and public authorities (Jacobides et al., 2016).

The first step of our empirical strategy was to identify the original equipment manufacturers (OEMs, i.e. the carmakers) that operate in the industry. To do so we drew on a set of four indicators each capturing specific dimensions of a firm's performance: (1) firms' revenues and (2) production, to account for a firm's commercial and manufacturing strength; (3) market capitalization to infer the market value of a firm's equity and (4) patenting activity as a proxy for a firm's inventive capability. This approach enabled us to simultaneously consider the characteristics of the different strategic groups that operate in the industry, thus including firms with very distinct profiles and market positioning. We collected information on these indicators from multiple sources, i.e. Orbis Bureau Van Dijk as far as revenues and market capitalization are concerned, the International Organization of Motor Vehicle Manufactures (OICA) for data on production, and the Orbit database by Questel to gather information on firms' patenting activity (measured as the cumulative number of granted patent families). For all these indicators, we then computed the firms' average value in the period 2011-2016. The union of the rankings of firms ordered by each of these indicators lead to the identification of the top 25 OEMs included in our study[4]. These firms represent 90% of the automotive OEMs industry production suggesting that through the analysis of their inventive activity we are able to capture the most relevant technological trends of this industrial context.

The second step of our methodology is to map the evolution of the knowledge base of the top OEMs. To do so, we follow established innovation literature (e.g., Patel and Pavitt, 1991; Grandstrand et al., 1997) and use patents – and, specifically, patent families - to trace their technological knowledge.

Mapping an industry's bodies of knowledge by reconstructing the patent portfolio of its most important players might be problematic, as companies often feature considerable levels of business diversification that might generate distortions in the data (e.g., Gambardella and Torrisi, 1998). In our empirical setting, we deem this risk as negligible since the limited business diversification of most automotive carmakers helps establishing relatively direct linkages between their knowledge base and the relevant industrial scope.

A major risk to bear in mind when using patent data is to not miscalculate firms' inventive capability due to the frequent practice of firms to apply for patent protection in different countries. To account for this potential bias, we rely upon the *patent family* definition, grouping together all patents pertaining to the same invention by means of a common priority filing (Martinez, 2010)[5]. Compared to the analysis of single patent documents, this methodological approach enables to consolidate multiple patents protected by

---

[4] The top 25 OEMs (ordered by aggregated number of patent families) included in our study are: Toyota, Hyundai, Honda, Nissan, Volkswagen, M, Ford, Daimler, Renault, Kia, Mazda, Peugeot, Geely, Mitsubishi, Suzuki, BMW, Fiat, Dongfeng, Changan, Chrysler, Great Wall, Baic, Saic, Tata, Tesla.

[5] Based on the European Patent Office (EPO)'s strict family rule, the Orbit FamPat database aggregates patent records from many Patent Offices across the world having exactly the same priority or combination of priorities (equivalents). Since each patent document is assigned to only one group, no single patent number may appear in two distinct families. Orbit adopts the strict family of EPO as a basis for the FamPat family but complements this definition with other additional information from various patent offices around the world. Therefore, although based on the same concept, the family structure of Orbit is broader than the EPO strict family definition.

different authorities in different geographies, but related to the same invention without overestimating the scope of firm knowledge (Alcácer and Zhao, 2012). In addition, it addresses possible structural lack of information in patent documents (De Rassenfosse et al., 2013).

Patent data have been collected from the Orbit database by Questel. This database allows to aggregate patents belonging to a given focal firm across its entire corporate tree[6], thereby accounting for the inventive activity of both the parent company and its subsidiaries. To ensure that such aggregation mechanisms are correct, we systematically processed and cleaned the information via customized algorithms aimed at identifying and fixing potential problems related, for example, to patent assignment errors. Thanks to this technique, we are quite confident that our data offer a rather comprehensive and reliable account of an organization's innovative output regardless of the unit that developed the specific invention and of internal conventions in the management of the patent application process.

The resulting dataset comprises 412,050 patent families granted over a 25-year period (1990-2014). A typical caveat in the analysis of patent data is the right truncation problem that reduces the number of observations in more recent years due to the length of the examination procedure (estimated to last an average of 18 months, cfr. Braun et al., 2011) and the resulting lag between the patent application and granting date. To mitigate this issue, we collected the data imposing a cut-off date at December 31st, 2016 but we retained for the analysis only patent granted up to 2014. Still, the data after 2013 reflect the right truncation problem and decline abruptly in 2014, as the general increase in patenting is making the granting process slower.

Patent documents include bibliographic and technical information such as the applicants, the inventors and the technical content of inventions, which allow to analyze important aspects of the underlying process of knowledge recombination, along with firms' and industries' competence accumulation patterns (Patel and Pavitt, 1991) and, more

---

[6] To consolidate patents at the corporate-tree level, Orbit relies on Factset that uses a variety of data sources. Primary sources are 10K, 20F and annual reports, transactions, such as mergers and acquisitions, company URL and use the internet as a third-party source. Furthermore, FactSet maintains entity hierarchies that are operational in nature, reflecting underlying regulatory, financing, and economic activities. Legal hierarchies are not currently supported. As concern *Public vs. non-public subsidiaries*, if a public company is owned more than 50% by another company, the entity will be classified as public because it is an actively traded company. The entity that owns over 50% of the public entity would be listed as its parent. Subsidiaries are those entities that are owned more 50% by another company and are not publicly traded. *Individuals* can be part of an entity's parent hierarchy when it is determined through ownership collection operations that an individual owns a majority stake in a company. Given these rules, we kept Chrysler and Fiat as separated entities since their merger occurred in the last year of our sample, 2014. As far as Hyundai and Kia are concerned, we rely on Orbit that classifies these firms as separated entities since the percentage of ownership of Kia by Hyundai is below the threshold of 50%.

generally, to better understand the process of technical change (e.g. Griliches, 1990; Tseng et al., 2011) as patents can be used to anticipate emerging trends and to capture the evolution of technologies over time (Ernst, 1997). Particularly relevant for this study is the analysis of the technological classes reported in patents (e.g., International Patent Classification, Cooperative Patent Classification). A longitudinal map of these classes allows to describe the evolution of technologies over time at different granularity levels, identifying - for instance - which technological domains are gaining momentum or are declining, and which firms are driving these trends. This analysis is possible due to the availability of yearly information on patents granted by different authorities in different geographies.

4.2 Data analysis

To explore the evolution of the *bodies of knowledge* of the automotive industry, we analyze the patent production of the top 25 automotive OEMs over time, with a focus on the information arising from these patents' technological classification. This type of analysis enables to reconstruct the technological domains in which the OEMs have generated new knowledge and accumulated competencies over a 25-year period (1990-2014).

In the first part of the analysis, we apply the Schmoch classification (Schmoch, 2008)[7] to OEMs' patent portfolios in order to identify the technological domains in which their inventive activity has focused in the period 1990-2014. This classification seeks to "*establish a concordance between technologies and sectors in order to show how technological competence is transferred into economic performance*" (Schmoch, 2008; p. 2). Thus, it is useful to understand the extent to which the inventive effort of carmakers has aimed at strengthening their capabilities in technological domains that are distinctive of their core product (i.e., *stability*), as opposed to developing knowledge in areas that are relatively less related to the industry's core technologies (i.e., *change*). This classification aggregates patents' technological classes (i.e., International Patent Classes, IPCs) in 35 technological fields that are further grouped into 5 main sectors: *Electrical engineering*, *Instruments*, *Chemistry*, *Mechanical engineering*, and *Other fields*.

[7] To identify the 35 technological fields of the Schmoch's classification we used the World Intellectual Property Organisation (WIPO) concordance table (version march 2018) that links the International Patent Classification (IPC) to the Schmoch's technological fields. For a complete description of the fields see: Schmoch, U. (2008). Concept of a technology classification for country comparisons. *Final report to the world intellectual property organisation WIPO*.

In the second part of the analysis, we undertake a similar exercise, but we use an alternative approach to assess the industry's focus on its core technological fields. Specifically, we rely on Ménière et al. (2018), who exploit the specialized knowledge of the European Patent Office's (EPO) examiners to identify the so-called *established* automotive technologies, i.e., "*all the technologies that can be found in today's mass-produced vehicles which do not include the features of connectivity and automated driving*" (Ménière et al., 2018; p. 53). Moreover, we seek to identify the technologies that, while lying outside of the automotive distinctive domains, have registered a meaningful and persistent increase in carmakers' patent stock and, thus, might be associated to the emergence of opportunities that could shape the industry's evolution. We label these fields as *high opportunity* technologies.

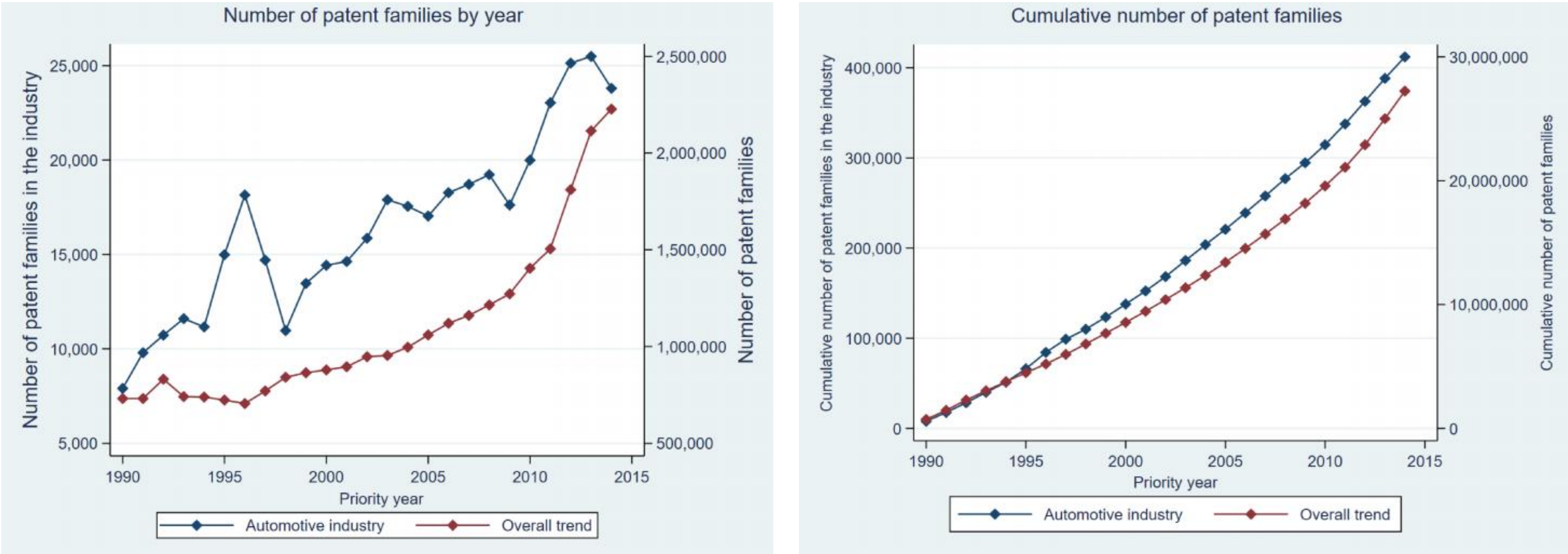
To carry out the above-mentioned analyses, we rely on the priority year reported in patents as reference date for the invention since, compared to the publication date, it is closer to the firm's actual inventive effort. This approach allows to trace the temporal aspect of knowledge generation despite the time lags caused by the patent examination process. Moreover, we monitor the evolution of technologies at different granularity levels using as a basic indicator the count of patent families in each technological domain. Absolute numbers are complemented with the analysis of (a) patent shares in each technology, both cumulatively and on a yearly basis, to uncover the relative inventive output in each technology, and of (b) patent growth rates, to highlight trends in technology evolution.

5. Results

5.1 Mapping the automotive knowledge base using the Schmoch's classification

Figure 1 represents OEMs' patenting activity over the period 1990-2014 both on a yearly basis (left panel) and cumulative (right panel), in comparison with the growth of the worldwide aggregate patenting activity. The right panel of this figure shows that the cumulative patenting activity of the industry is consistent with the general increase in worldwide patenting during the period of analysis. The left panel documents overall a growing trend, despite the inflections registered following the Korean financial crisis of 1997 – which had major effects on the patent production of Hyundai and Kia – and the global financial crisis of 2008-2009. As anticipated, after 2013, the data reflect the right truncation problem that is typical of analyses based on granted patents, which are affected by the length of examination procedures.

Figure 1. Evolution of patenting activity in the automotive industry in the period 1990-2014.



As anticipated above, the first set of analyses of the technological domains to which these inventions belong is based on the Schmoch classification, regularly updated by the World Intellectual Property Organisation (WIPO). In order to perform this analysis, we assign patent families to the Schmoch technological fields based on the distinct IPCs they cite, in order to account for the fact that a single invention might be relevant for more than one field. Because most patent families cite different IPCs and, accordingly, are assigned to different fields, the sum of patent families in different fields by definition does not equal the total amount of patent families in our dataset, but is instead much greater.

Table 1 reports the number and percentage of patent families in the 35 fields of the Schmoch classification, further aggregated in 5 sectors.

As expected, at the broader sector level, OEMs' innovative activity is largely concentrated in the *Mechanical Engineering* sector that includes technological fields that represent the core competences of the industry since its inception (Schultze et al., 2015). Within this sector, three major technological fields emerge. The first one is the field of *Transport*, covering all types of transport technologies and applications in the automotive domain, where the bulk of the patenting activity of the industry (45.12%) concentrates. The *Engines, Pumps and Turbines* field, covering non-electrical engines for all types of applications including the automobiles, follows with a percentage of 20.0%. *Mechanical Elements*, including all engineering elements of machines and the control devices (i.e. joints, couplings, pipe-line systems), is the third most important field, and represents the 15.07% of the patenting activity of the industry. The concentration of patenting activity in these domains suggests that these are technologies that strongly characterize the inventive activity and *bodies of knowledge* of the industry.

The second most important technological sector by patenting activity is the *Electrical Engineering* one, including fields relating to power machines and power generation. Within this realm, the *Electrical Machinery, Apparatus and Energy* field - covering the generation, conversion and distribution of electric power, machines and other basic elements such as resistors, magnets and cables - is particularly important, as it is cited by 11.70% of granted families, thus being the fourth most important field by patenting activity.

The other three sectors of the Schmoch classification are relatively less populated. Yet, some of their individual fields are quite relevant, such as *Measurement* (included in the *Instruments* sector, and covering a broad variety of techniques and applications such as the measurement of mechanical properties as oscillation or speed), *Environmental Technology* (included in the *Chemistry* sector and dealing with the use and development of filters, waste combustion and silencers), which are cited respectively by 7.65% and 5.15% of the families in our database.

Table 1. Patenting activity of the automotive industry by technological fields of the Schmoch's classification in the period 1990-2014.

Frequencies and percentage of patent families by technological fields of the Schmoch's classification			
Sector description	**Field description**	**Num. fam.**	**% of tot industry families**
Mechanical engineering	Transport	185,910	45.12
Mechanical engineering	Engines, pumps, turbines	82,422	20.0
Mechanical engineering	Mechanical elements	62,088	15.07
Mechanical engineering	Machine tools	21,297	5.17
Mechanical engineering	Handling	8,661	2.10
Mechanical engineering	Other special machines	8,540	2.07
Mechanical engineering	Thermal processes and apparatus	5,217	1.27
Mechanical engineering	Textile and paper machines	1,839	0.45
Electrical engineering	Electrical machinery, apparatus, energy	48,221	11.70
Electrical engineering	Computer technology	14,806	3.59
Electrical engineering	Telecommunications	6,799	1.65
Electrical engineering	Audio-visual technology	6,473	1.57
Electrical engineering	Semiconductors	5,973	1.45
Electrical engineering	Digital communication	5,578	1.35
Electrical engineering	IT methods for management	1,678	0.41
Electrical engineering	Basic communication processes	1,341	0.33
Instruments	Measurement	31,527	7.65
Instruments	Control	19,100	4.64
Instruments	Analysis of biological materials	4,590	1.11
Instruments	Optics	2,493	0.61
Instruments	Medical technology	2,013	0.49
Chemistry	Environmental technology	21,220	5.15
Chemistry	Chemical engineering	12,297	2.98
Chemistry	Materials, metallurgy	10,455	2.54
Chemistry	Surface technology, coating	8,584	2.08
Chemistry	Basic materials chemistry	2,805	0.68
Chemistry	Macromolecular chemistry, polymers	2,479	0.60
Chemistry	Organic fine chemistry	922	0.22
Chemistry	Biotechnology	646	0.16
Chemistry	Food chemistry	547	0.13
Chemistry	Micro-structural and nano-technology	535	0.13
Chemistry	Pharmaceuticals	340	0.08
Other fields	Civil engineering	13,851	3.36
Other fields	Furniture, games	3,205	0.78
Other fields	Other consumer goods	2,485	0.60
Tot industry families		**412,050**	

Figure 2 represents the evolution over time of the patenting activity in the technological fields of the Schmoch classification included in the sectors of *Mechanical Engineering*, *Electrical Engineering*, *Instruments* and *Chemistry*[8].

At the sector level, *Mechanical Engineering* shows the most unstable pattern in the period of analysis, reflecting the effects of both the Korean recession and the global financial crisis in a more substantial way compared to other sectors, as it is predictable given its greater absolute weight. At the field level, technologies related to *Transport* registers the greatest growth trend along the entire period of observation, suggesting that OEMs steadily continue to accumulate competencies in the technological domain that is probably the most distinctive of the industry's knowledge base. We interpret this as a first evidence of the stability that characterize the knowledge base of the industry. Other technologies related to *Engines, Pumps and Turbines* are quite stable along the period of observation following a pattern similar to technologies related to *Mechanical Elements*.

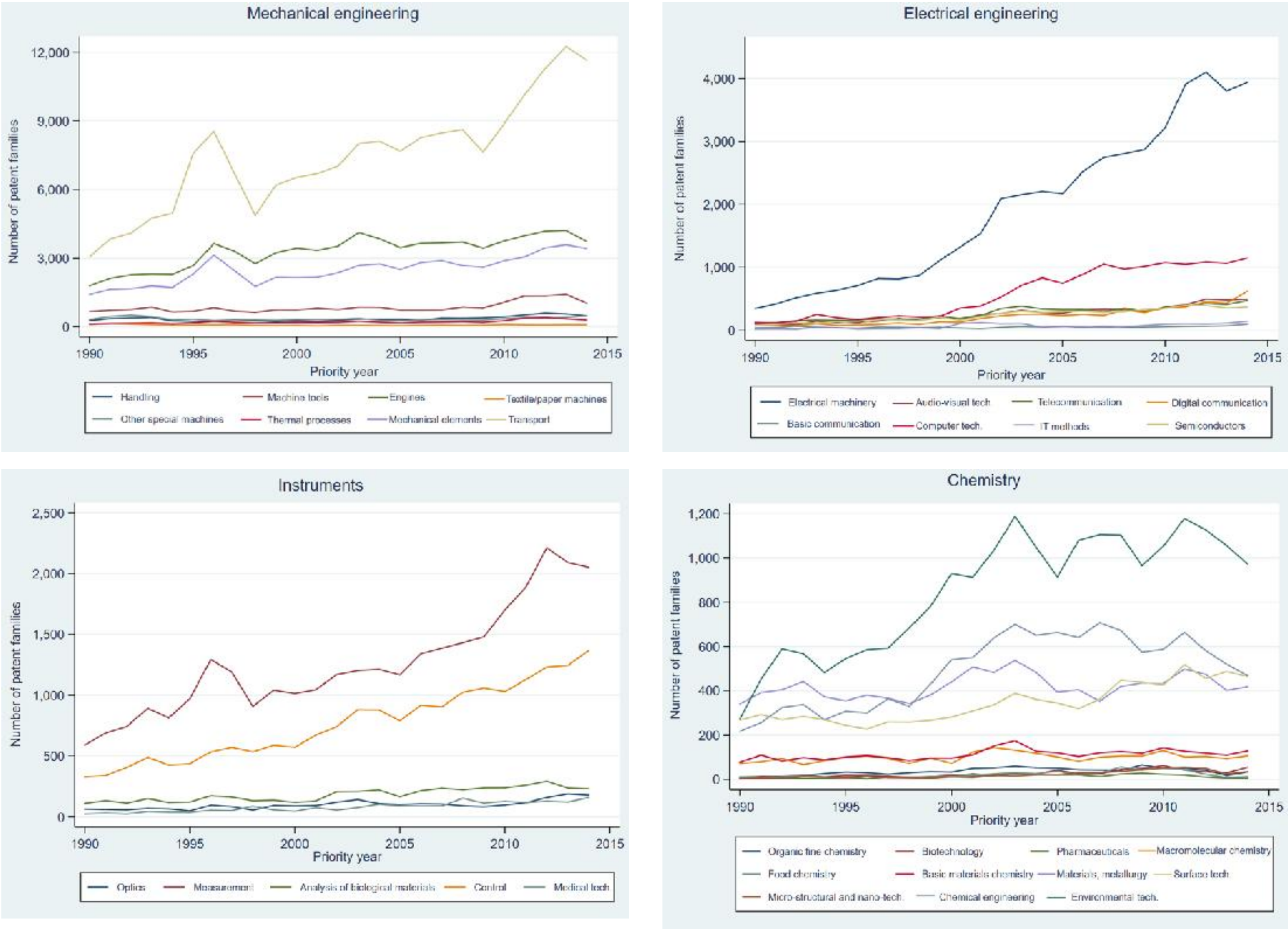
Within the *Electrical engineering* sector, the field of *Electrical Machinery, Apparatus and Energy* shows a very sustained increase in the number of patent families over time, offering a first evidence of OEMs' growing effort to develop technological competencies that may help them facing the electrification challenge. While very different in absolute numbers compared to the *Electrical Machinery, Apparatus and Energy* domain, other technological fields in this sector register very significant growing trends: first and foremost, the *Computer Technology* field, but also the *Digital Technology*, *Telecommunication*, *Audio-visual Technology* and *Semiconductor* fields. These fields enter the period of analysis as barely represented and, starting from the late 1990s, grow in importance –although at different speed rates– through almost the remained of the period, providing evidence of OEMs' experimentation in technical domains that are more distant from the technological core of the industry.

Within the *Instruments* sector, it is worth highlighting the increasing trend of both the *Measurements* and *Control* fields, whereas other fields within this sector show a rather stable pattern along the entire period considered.

Finally, within the *Chemistry* sector, the *Environmental Technology* field grows in importance until the early 2000s, but seems to stabilize in the last decade of our analysis.

[8] We excluded the "*Other Fields*" because of its internal heterogeneity as well as its limited weight in OEMs' patenting activity.

Figure 2. Patenting activity in the period 1990-2014 by technological fields of the Schmoch's classification.



To complement the previous descriptive analysis of the dynamic evolution of OEMs' patenting in different technological fields, *Table 2* shows the average annual growth rate of the top 10 *fields* by number of patent families across subsequent 5-year periods. The majority of fields display their highest growth in the periods 1990-1994 and 1995-1999 and stabilize at lower rates in the following periods. This is particularly the case for the *Environmental Technology* field, highlighting a substantial increase through all periods (except for the 2005-2009) but a particularly high growth rate of 18.36% in the period 1990-1994. Other key fields of the industry, like *Engines, Pumps, Turbines* and *Mechanical Elements* show similar trends, along with *Measurement* and *Control* which nonetheless feature a slightly higher growth in the period 1995-1999. Moving to technological fields whose original importance in OEMs' patenting activity was relatively limited, perhaps the most interesting trends are associated to the *Computer Technology* and the *Electrical Machinery, Apparatus, Energy* fields. These technologies have a significant growth already in the first period, with an average growth rate of respectively 14.92% and 21.04%, but register an even greater surge of 15.38% and 31.48% respectively in the period 2000-2004.

While *Table* 2 allows to compare the growth rates of the top 10 technological fields by patenting activity over the entire period of analysis, *Table 3* shows how the ranking of the top 10 fields changes if computed across distinct 5-year periods. Given the zoom into the 10 most populated technological fields, this table allows us to detect the variability in OEMs' technological focus over time. On the one hand, it is possible to observe the substantial stability of the top three positions of the ranking, which are occupied by fields corresponding to technological domains that are highly specific of the automotive industry, namely (1) *Transport*, (2) *Engines*, *Pumps*, *Turbines*, and (3) *Mechanical Elements*. Such stability can be detected along all periods, with the exception of the last period of analysis (2010-2014) in which the *Electrical Machinery, Apparatus and Energy* field gains the 3^{rd} position (climbing the ranking from the 7^{th} position in the first period of analysis), replacing the *Mechanical Elements* field. On the other hand, some technological fields (namely, *Civil Engineering*; *Other Special Machines*; *Materials*, *Metallurgy*; *Chemical Engineering*) register a more discontinuous presence, entering the ranking only in specific 5-year periods. Finally, it is worth mentioning the dynamics of the *Computer Technology* field, which enters the ranking for the first time in 2000-2004 and increases its importance over the two subsequent periods, climbing from the 10^{th} to the 8^{th} position.

Table 2. Growth rate of the patenting activity of the automotive industry in the period 1990-2014 by technological sector and field of the Schmoch's classification.

Number of patent families and average growth rate of the top 10 Schmoch's fields (by aggregated number of families) over 5-year period										
	1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field description	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**
Transport	20,718	12.01	33,886	8.68	36,391	5.63	40,692	-0.96	54,223	9.10
Engines, pumps, turbines	10,765	6.70	15,623	8.92	18,275	3.77	17,932	-2.00	19,827	1.83
Mechanical elements	8,241	5.15	11,813	8.64	12,112	5.05	13,503	-0.77	16,419	5.80
Electrical machinery, apparatus, energy	2,502	14.92	4,327	12.10	9,305	15.38	13,119	5.63	18,968	6.93
Measurement	3,730	9.16	5,403	7.09	5,646	3.23	6,807	4.21	9,941	7.14
Machine tools	3,637	3.58	3,555	3.94	3,987	3.00	3,873	-0.09	6,245	6.85
Environmental technology	2,365	18.36	3,189	10.22	5,112	6.72	5,169	-0.99	5,385	0.46
Control	1,988	7.47	2,666	7.10	3,748	8.73	4,694	4.24	6,004	5.40
Computer technology	848	21.04	1,045	2.46	2,811	31.48	4,676	4.75	5,426	2.62
Civil engineering	2,912	12.88	2,478	1.99	2,596	3.43	2,881	-1.19	2,984	3.1

Table 3. Ranking of the top 10 technological fields of the Schmoch's classification by number of patent families in the period 1990-2014.

Ranking of the top 10 fields of the Schmoch's classification over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field description	**% of patent families over the period**	**Field description**	**% of patent families over the period**	**Field description**	**% of patent families over the period**	**Field description**	**% of patent families over the period**	**Field description**	**% of patent families over the period**
Transport	40.48	Transport	46.90	Transport	45.30	Transport	44.79	Transport	46.17
Engines, pumps, turbines	21.03	Engines, pumps, turbines	21.63	Engines, pumps, turbines	22.75	Engines, pumps, turbines	19.74	Engines, pumps, turbines	16.88
Mechanical elements	16.10	Mechanical elements	16.35	Mechanical elements	15.08	Mechanical elements	14.86	Electrical machinery, apparatus, energy	16.15
Measurement	7.29	Measurement	7.48	Electrical machinery, apparatus, energy	11.58	Electrical machinery, apparatus, energy	14.44	Mechanical elements	13.98
Machine tools	7.11	Electrical machinery, apparatus, energy	5.99	Measurement	7.03	Measurement	7.49	Measurement	8.46
Civil engineering	5.69	Machine tools	4.92	Environmental technology	6.36	Environmental technology	5.69	Machine tools	5.32
Electrical machinery, apparatus, energy	4.89	Environmental technology	4.41	Machine tools	4.96	Control	5.17	Control	5.11
Environmental technology	4.62	Control	3.69	Control	4.67	Computer technology	5.15	Computer technology	4.62
Other special machines	3.91	Civil engineering	3.43	Chemical engineering	3.83	Machine tools	4.26	Environmental technology	4.58
Control	3.88	Materials, metallurgy	2.52	Computer technology	3.5	Chemical engineering	3.59	Civil engineering	2.54

Overall, these findings provide a first evidence supporting the idea that the lens of change and stability properly describes knowledge generation and capability development in the automotive industry.

5.2 Mapping the automotive knowledge base using the IPC classification: "established" vs. "high opportunity" technologies

In this paragraph, we zoom into the different technological *sectors* and *fields* analyzed above and lower the level of the analysis through the use of a more disaggregated classification. To this purpose, we exploit the information about technological classes reported in patent documents using the International Patent Classification (IPC)[9]. Patent families within our sample are associated to 667 unique IPC 4-digit classes (hereafter, IPC). The majority of patent families cite one IPC classes (50.53%) whereas about 26.10% cite two IPC classes. The average number of IPC classes embedded in patent documents slightly increases over time, ranging from an average of 2.4 IPC codes per family in 1990 to an average of 2.8 IPCs per family in 2014 as reported in *Table 4*. This suggests that the underlying inventions are relevant for different technological areas. Moreover, it may indicate an increase in the number of technical domains that are recombined within patents. In line with the extensive literature on knowledge recombination (Fleming and Sorenson, 2001), a higher degree of knowledge recombination within patents families reveals a pattern of cross-technology fertilization leading to a higher technological complexity of inventions.

Our IPC-level analysis aims at identifying and exploring two types of technologies that we consider important to understand the evolution of the industry's knowledge base given the stability and change lens adopted in this study: (1) the core technologies that characterize the industry, labelled as "established" automotive technologies, and (2) the originally unrelated technologies that have gained momentum over the period of analysis, which we label "high opportunity" technologies. Compared to the approach adopted in Section 5.1., using the finer-grained IPC classification allows us to be more precise in selecting, among the set of inventions developed by OEMs in the period 1990-2014, those that signal stability as opposed to those indicating change.

[9] To identify the "established classes", we use IPC-CPC conversion table provided by WIPO. CPC is an extension of the IPC classification and has been used by the EPO (2018) for the identification of the "established" technologies of the automotive industry. In particular, the class F16D48 referring to technologies related to external control of clutches has been flagged as established and it is an extension of F16D 4-digit IPC class which includes technologies related to couplings for transmitting rotation.

Table 4. Average number of IPC per patent family between 1990-2014.

Average number of IPC per patent family over time	
Year	**Average num. IPC**
1990	2.45
1991	2.39
1992	2.35
1993	2.40
1994	2.35
1995	2.19
1996	2.15
1997	2.44
1998	2.69
1999	2.63
2000	2.68
2001	2.76
2002	2.79
2003	2.93
2004	2.85
2005	2.76
2006	2.71
2007	2.78
2008	2.67
2009	2.83
2010	2.79
2011	2.75
2012	2.69
2013	2.72
2014	2.83

5.2.1 An analysis of the "established" automotive technologies

Investigating the "established" automotive technologies helps to shed more light into whether and how the core technological domains of the automotive industry have maintained their primary role in OEMs' knowledge base. To investigate the "established" automotive technologies, we follow the approach by Ménière et al. (2018), who exploit the specialized knowledge of patent examiners to classify as "established" "*all the technologies that can be found in today's mass-produced vehicles which do not include the features of connectivity and automated driving*" (Ménière et al., 2018; p. 53).

Table 5 exhibits the set of IPCs included in this definition with the indication of the number and percentage of patent families in each class. These IPCs are associated to technologies that have been traditionally at the core of the automotive industry as vehicles parts, motor components, propulsion systems, combustion engines and conjoint controls.

As it is possible to note from *Table 5*, most of the innovative activity within the established classes, relates to the two macro areas of *Transporting* (classes included in group B of the IPC scheme, as indicated by the first digit of the IPC code) and of *Mechanical Engineering, Lighting and Heating* (classes included in group F of the IPC scheme). An exception is the class related to the electrical component of the automobiles within the group H of the IPC classification. Overall, the patent families in "established" automotive technologies comprise 56.61% of the OEMs' patenting activity in the entire period of analysis, which points to the strong engineering and mechanical competences that firms need to master to operate in the industry.

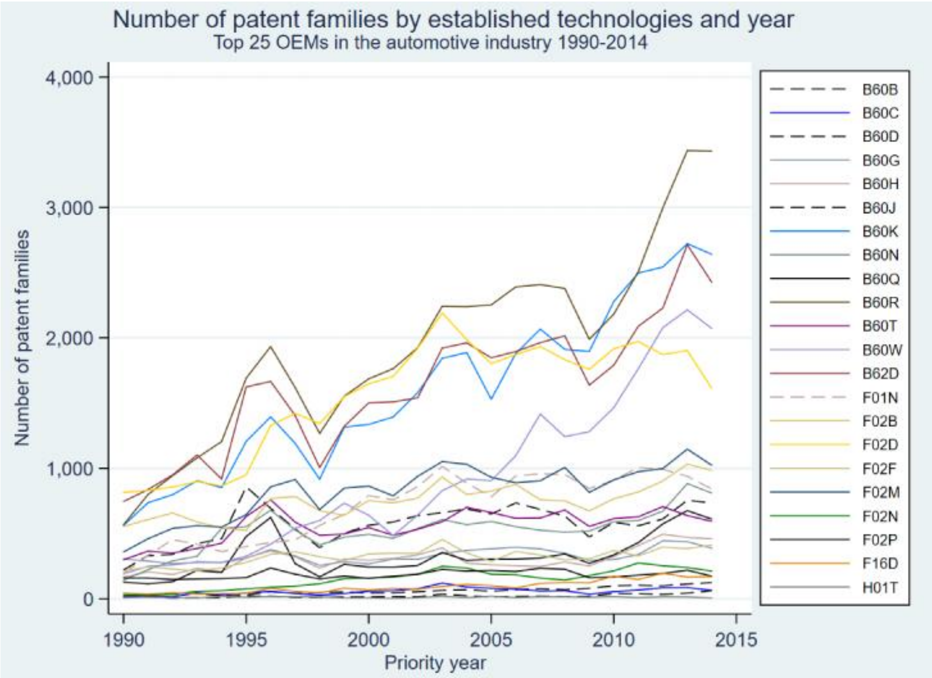
The evolution of OEMs' patenting activity in these technologies (measured in terms of number of patent families by consecutive year and cumulative), displayed in *Figure 3*, highlights that the number of patent families in a large majority of the established automotive technologies has been increasing in the period of analysis, consistent with the idea that accumulating competences in the technological core of the industry is key to survival and, in turn, serves a major source of industry stability. Specifically, technological classes related to *Propulsion Systems* (B60K), *Motor Vehicles* (B62D) and *Vehicles Parts* (B60R) have a growing number of patent families since 1990, although with some variation mainly reflecting the changing macroeconomic environment. Instead, technologies related to *Conjoint Control*, (B60W) exhibit a more pronounced increase starting from 1996, and show an even higher upward trend after 2003. Another group of technologies related -for instance- to *Vehicle Wheels* (B60B) and *Brake Control Systems* (B60T) show a peak in 1995 and later on stabilize until the final years of our analysis. A last group of technologies, such as those related to the *Starting of Combustion Engine* (F02N) and *Over Voltage Arresters Systems* (F16D) have a relatively lower number of patent families along the entire period considered. Interestingly, the only class that shows a significant decrease in the number of patent families granted to OEMs over time is *Combustion Engines* (F02D), whose importance tends to decrease after the peak in new granted families reached in 2003.

Table 5. Patenting activity in "established" automotive technologies.

IPC classes corresponding to *established* automotive technologies*			
Class	**Description**	**Num. families**	**% over tot. industry families**
B60R	Vehicles, vehicles fitting, vehicles parts	48,476	11.76
B62D	Motor vehicles, trailers	40,598	9.85
B60K	Arrangement or mounting of propulsion units of transmission in vehicles	39,870	9.68
F02D	Controlling combustion engines	38,766	9.41
B60W	Conjoint control	22,932	5.57
F02M	Supplying combustion engines (carburettors, fuel injection)	20,697	5.02
F02B	Internal combustion piston engines	18,728	4.55
F01N	Exhaust Apparatus (gas flow silencers or exhaust apparatus)	17,732	4.30
B60J	Protective coverings specially adapted for vehicles (window, windscreen)	14,327	3.48
B60T	Vehicle brake control systems or parts thereof	13,966	3.39
B60N	Seats specially adapted for vehicles	13,106	3.18
B60G	Vehicle suspension arrangements	8,295	2.01
B60Q	Signaling and lighting	8,162	1.98
F02F	Cylinders, pistons, casings for combustion engines	8,073	1.96
B60H	Arrangement of adaptions of heating	7,614	1.85
F02P	Ignition	4,645	1.13
F02N	Starting of combustion engines	3,808	0.92
F16D48	Clutches controls	2,357	0.57
B60B	Vehicle wheels	1,570	0.38
B60C	Vehicle tires	1,439	0.35
B60D	Vehicle connections	565	0.14
H01T	Spark gaps, overvoltage arresters using spark gaps	334	0.08
Tot. patent families		**233,249**	**56.61**
Tot. industry patent families		**412,050**	

*According to the EPO (2018: 53), "*established automotive technologies comprise all the technologies that can be found in today's mass-produced vehicles which do not include the features of connectivity and automated driving*".

Figure 3. Evolution of patenting activity of the automotive industry in "established" technologies in the period 1990-2014.



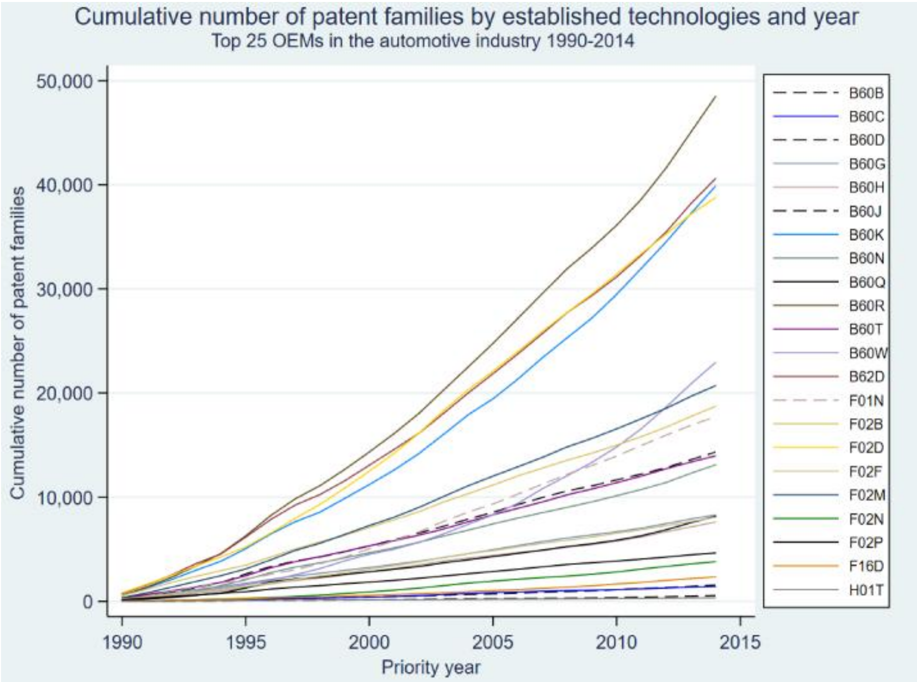


Table 6 displays the ranking of the top 5 “established” classes over 5-year periods reporting the percentage of the number of families in these classes over the total number of families in the period. It is worth noting that only two classes enter the ranking across all periods. The first one is *Combustion Engines* (F02D), whose position varies significantly from the being the 1st in the period 1990-1994 to become the 5th and last of the ranking in the last period of analysis 2010-2014. This is consistent with the trend highlighted in Figure 3, which seems to suggest that OEMs tend to reduce their investment in the exploitation of the traditional method for powering cars, most likely to devote greater attention to more sustainable solutions. It is also in line with the trend characterizing the classes *Internal Combustion Piston Engines* (F02B) and *Supplying Combustion Engines (carburettors, fuel injection)* (F02M) which enter the ranking - respectively – only in the early periods of analysis, but lose importance in the remaining time intervals.

The second class to enter the ranking in all periods is *Propulsion system*s (B60K), which shows an increase in the number of patent families in the last period of analysis. *Motor Vehicles* (B62D) and *Vehicle Parts* (B60R) enter the ranking in the second period (1995-1999), and the latter remains the top class in all remaining periods. Similarly, *Conjoint controls* (B60W) enters the ranking in the period 2005-2009 and shows a growth in the percentage of patent families in the subsequent period 2010-2014.

To conclude our analysis of the “established” automotive technologies, we show how OEMs’ overall investment in these domains has changed over time, in order to provide a general assessment of the extent of stability of the automotive knowledge base. Specifically, *Table 7* displays both the absolute number of patent families that have been granted every year in “established” automotive technologies, and their relative weight on OEMs’ overall patenting activity, measured as the percentage of patent families in “established” automotive technologies over total patent families by year. As it is possible to notice, “established” automotive technologies represent 52.15% of OEMs’ overall patenting activity in the first year of our analysis (1990), and 56.20% of OEMs’ overall patenting activity in the last year of our analysis (2014), with a peak of over 60% in 2000 and never goes below the 51% lower bound. This seems to suggest that the importance of the “established” automotive technologies for OEMs’ inventive processes has increased over time. Moreover, it provides additional evidence supporting the idea that the knowledge base of the industry features a significant degree of stability, despite the experimentation that OEMs conduct outside of their traditional technological core, as demonstrated by the whole set of patent families that concentrate in other, non “established” IPCs, which tend to explain up to 49% of OEMs’ patenting activity.

Table 6. Ranking on the top 5 "established" technologies over time with percentage over the total number of families in each period.

Ranking of the top 5 established technologies over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Class	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**
F02D	8.34	B60R	11.16	B60R	12.26	B60R	12.57	B60R	12.39
B60K	7.53	B62D	9.72	F02D	11.76	B62D	10.3	B60K	10.79
F02B	5.77	F02D	9.12	B62D	10.49	B60K	10.22	B62D	9.57
F02M	4.83	B60K	8.34	B60K	10.0	F02D	10.12	B60W	8.17
B60T	3.57	F02M	5.47	F02M	5.82	B60W	6.54	F02D	7.89

Table 7. Evolution of OEMs' patenting activity in established technologies.

Number and percentage of established patent families by year (aggregated by year)			
Year	**Number of established patent families**	**Number of industry patents families**	**% over the industry families**
1990	4,123	7,906	52.15
1991	5,091	9,792	51.99
1992	5,541	10,725	51.66
1993	6,128	11,596	52.85
1994	6,280	11,160	56.27
1995	9,124	14,981	60.90
1996	10,621	18,145	58.53
1997	8,652	14,694	58.88
1998	6,376	10,965	58.15
1999	8,069	13,459	59.95
2000	8,660	14,418	60.06
2001	8,587	14,619	58.74
2002	9,133	15,855	57.60
2003	10,648	17,892	59.51
2004	10,457	17,546	59.6
2005	9,814	17,029	57.63
2006	10,701	18,269	58.57
2007	10,840	18,709	57.94
2008	11,009	19,223	57.27
2009	9,542	17,615	54.17
2010	10,869	19,991	54.37
2011	11,977	23,034	51.99
2012	13,339	25,136	53.07
2013	14,292	25,492	56.06
2014	13,376	23,799	56.20

5.2.2 An analysis of "high opportunity" technologies

The analysis of OEMs' patenting activity in the so-called "established" automotive technologies provides a dynamic picture of their investment in the technological competencies that have traditionally been at the core of the automotive industry. In order to complement this view, it is important to understand what are the new directions of invention in which the dominant actors of the industry have decided to concentrate their attention over time. To this aim, we seek to isolate the technologies that have gained particular importance in OEMs' patent portfolios and that are redirecting firms' inventive efforts, thereby potentially modifying the knowledge base of the industry.

To identify these new directions of invention, we adopt a methodological approach that enables us to detect those technologies that have been characterized by a remarkable and persistent growth in the period of analysis. This approach, which is inspired by the procedure developed by Cecere et al. (2014), is based on two steps. First, we compute the growth rates of the number of families across IPC classes over two-years periods, which enables us to control for peaks due to unobservable random factors that may affect the patenting examination procedure. Then, we identify those IPC classes that feature abnormal growth rates (i.e., above the average growth of the period) for at least 4 consecutive periods and that are cited in at least 200 patent families within our sample, in order to avoid focusing our attention on classes that have a too narrow representation in OEMs' overall patenting activity despite their substantial growth rates. We label the technologies corresponding to these IPC classes "high opportunity" technologies (cfr. Cecere et al., 2014).

Table 8 reports the IPCs that meet the abovementioned criteria[10] displaying some interesting technological trends. In particular, we observe a massive presence of technologies related to *electrification* (e.g., B60L, *Propulsion of Electrically-Propelled Vehicles*; H01M, *Processes or Means; e.g. Batteries for the Conversion of Chemical Energy into Electrical Energy*; H02J, *Circuits Arrangements or Systems for Supplying or Distributing Electric Power, Systems for Storing Electric Energy*) and *digital/networking* technologies (e.g., H04W, *Wireless Communication Networks*; G06F, *Electric Digital Data Processing*; G06K, *Recognition/Presentation of Data*), which appear to push OEMs' inventive efforts toward directions that were originally only tangential to the knowledge base of the industry.

[10] The criteria used in the identification of "high opportunity" technologies have been tested using different cut-off level for the number of patent families citing each IPCs classes as well as for the number of consecutive growth periods. The number of IPCs identified as "high opportunity" remains stable across the use of different approaches.

Table 8. Patenting activity in “high opportunity” technologies.

IPC classes corresponding to ***high opportunity technologies*** (ordered by periods of consecutive growth)				
Class	**Description**	**Periods of growth**	**Num. Families**	**% over industry families**
B82Y	Specific uses or applications of nanostructures; measurement/ manufacturing or treatment of nanostructures	8	276	0.07
H04W	Wireless communication networks	7	1,454	0.35
G06F	Electric digital data processing	6	10,549	2.56
G08G	Traffic control systems	6	9,526	2.31
H01M	Processes or means; e.g. Batteries for the conversion of chemical energy into electrical energy	5	23,351	5.67
B25H	Workshop equipment	5	343	0.08
G06K	Recognition/ presentation of data	5	1,642	0.4
B62K	Cycles, cycle frames, cycles steering devices	4	3,522	0.85
B60L	Propulsion of electrically-propelled vehicles	4	17,655	4.28
A61B	Diagnosis, surgery, identification	4	668	0.16
F02G	Hot-gas or combustion-product positive displacement engine plants; use of waste heat of combustion engines, not otherwise provided for	4	677	0.16
A61F	Filterd implantable into blood vessels, prostheses, devices providing patency to, or preventing collapsing of, tubular structures of the body	4	238	0.06
A61H	Physical therapy apparatus, devices for locating or stimulating reflex points in the body	4	336	0.08
E04H	Buildings or like structures for particular purposes	4	638	0.15
H02J	Circuits arrangements or systems for supplying or distributing electric power; systems for storing electric energy	4	6,806	1.65
C01B	Non-metallic elements; compounds thereof	4	2,139	0.52
Tot. Patent families			**65,466**	
Tot industry families			**412,050**	

Figure 4 exhibits the evolution over time of the patenting activity (i.e., captured in terms of the number of patent families citing each IPC class) in the "high opportunity" technologies. The technologies related to *electrification* clearly stand out with respect to the other technologies. In particular, technologies linked to the conversion from chemical to electrical energy through the use of *batteries* (H01M) show a sustained increase in the number of patent families starting already in the 90s'. This trend is linked to the increasing policy attention to environmental issues which translated, back in 1996 in California, in the introduction of the Zero Emission Vehicles (ZEV) mandate and consequent debut of the first version of the electric vehicle (Bergek et al., 2013). New stringent regulation on free emission have contributed to intensify the experimentation on costs, weight and performances of batteries (e.g. nickel versus lithium) as well as on technologies related to electrical power trains[11].

Figure 4 also shows that the technologies related to the *processing of electric digital data* (G06F) display similar trends, with a significant increase in the number of patent families up to 2006 and a substantial growth rate of the patenting activity in the period 2000-2004. Technologies related to the *Propulsion of Electrically-Propelled Vehicles* (B60L) also shows a surge in the number of patent families especially starting in 2008 with a peak in 2011.

[11] In this line, Flamand (2016), focusing on the analysis of the patenting activity of 13 automakers within the area of energy storage solutions, highlight that carmakers are unevenly involved in the development of these technologies with a distinct position in the value chain. Huth et al. (2013) stressed that the increasing importance of the battery module is expected to lead to a reconfiguration of the battery value chain for electrical vehicles with the classical make-or-buy decision for OEMs of which parts of the battery should be manufactured in house and which parts should be outsourced..

Figure 4. Evolution of patenting activity of the automotive industry in "high opportunity" technologies in the period 1990-2014.

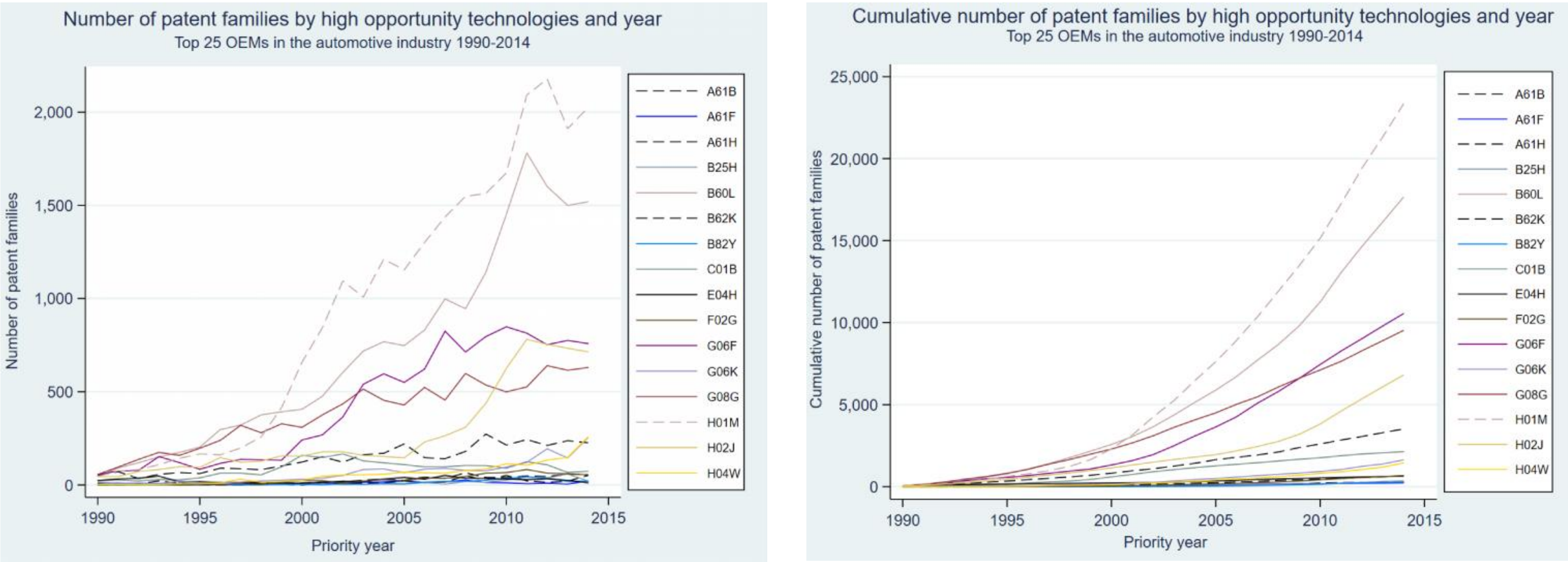


Table 9 shows the ranking of the patenting activity of the top 5 “high opportunity” technologies across different 5-year periods, to explore whether their relative importance is stable over time or vary depending on OEMs’ strategies or environmental factors. The ranking is quite steady across the different 5-year periods, with the technologies related to *electrification* in general and *batteries* (H01M) gaining the top positions in the ranking between 2000-2014. Interestingly, the only class unrelated to the electrification trend entering this ranking refers to *Traffic Control Systems* (G08G), which might be interpreted as evidence of OEMs’ consistent investment in domains that enable them to maintain and improve safety standards arising from the fact that cars are heavy objects that move in public space, potentially at high speed (MacDuffie and Fujimoto, 2010).

Overall, the analysis of the “high opportunity” technologies documents a significant experimentation in once-unrelated domains that, as suggested by previous literature, are mainly driven by OEMs’ need to respond to governmental regulations in the realm of both emissions and safety (Bergek et al., 2013; MacDuffie and Fujimoto, 2010; Schultze et al., 2015).

Table 9. Ranking of the top 5 high opportunity technologies over time.

Ranking of the top 5 *high opportunity technologies* over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Class	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**
G08G	1.22	B60L	2.20	H01M	5.99	H01M	7.71	H01M	8.41
B60L	1.14	G08G	1.89	B60L	3.7	B60L	5.13	B60L	6.68
G06F	0.94	H01M	1.66	G08G	2.6	G06F	3.86	G06F	3.36
H01M	0.89	H02J	0.9	G06F	2.5	G08G	2.8	H02J	3.07
H02J	0.67	G06F	0.84	H02J	1.02	H02J	1.53	G08G	2.48

5.3 Technological diversification in the industry

We also analyze the annual patterns of technological diversification using the Herfindhal index of the total number of patent families in the technological domains identified by both the Schmoch's and the IPC classification. The Herfindahl index is extensively used in the patent literature to measure the degree of concentration of patent families across technological domains (Gambardella and Torrisi, 1998). In the context of our study, this index helps to detect any significant variation in OEMs' approach to experimentation, which should be captured by changing levels of diversification over time.

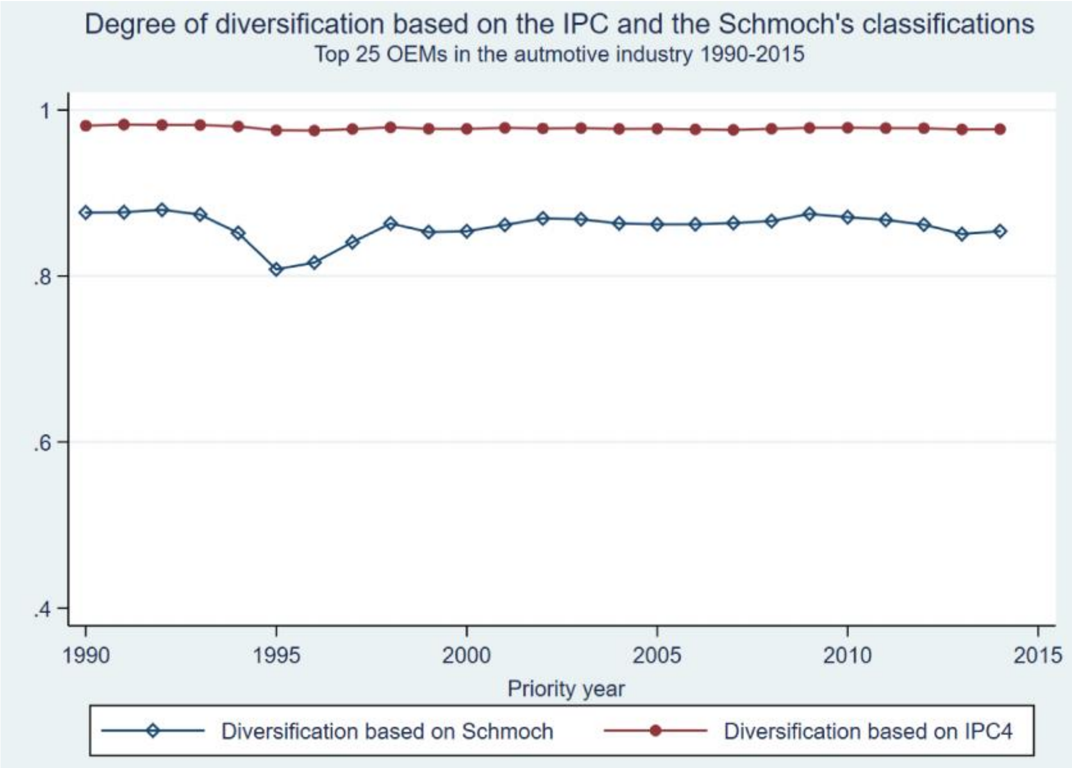
The index ranges between 0, when patent families are evenly dispersed over large number of technological domains, and 1 when patents are based on only one domain. We transform the Herfindhal index into a measure of diversification by taking its complement (i.e., 1-Herfindhal Index) with higher values of the index corresponding to higher level of technological diversification of the industry's patent families in different technical domains. This index represents a more accurate measure of technological diversification relative to a simple count of technologies of a firm's knowledge base, since the latter is very sensitive to accidental discoveries in particular technological fields.

Table 10 reports the annual diversification values computed on the Schmoch technological fields as well as on the IPCs classes. A first aspect to stress is that the level of technological diversification in OEMs' patenting activity is very high through all the period of analysis, showing a consistent commitment to invent across different technological domains. The level of industry diversification tends to slightly decrease over time, a trend that is more evident in the index using the Schmoch classification. Because the latter aggregates technological classes in 35 broader fields, changes in diversification index based on this classification are more likely to capture meaningful variations in the scope of the industry's knowledge, compared to changes in the index based on the IPC classification (which instead is much more disaggregated comprising over 600 fields). Overall, the dynamic variation of the index is minimal, and ranging between 0.87 and 0.85 during the whole period. *Figure 5* shows the trends of diversification over time highlighting a limited drop of diversification in 1995, based on the Schmoch classification, which then stabilizes with any substantial variation over the remaining period of analysis. Combined with the previous findings of our study, this evidence seems to provide further evidence of the systematic balance between the need to experiment in new and unrelated technological domains and the importance of strengthening existing competences in the industry's technological core. To some extent, the two dynamics seem to feed one another. In fact, for OEMs to be able to integrate potential technological opportunities arising from experimentation within a very complex product architecture such as that of cars, a sustained investment in knowledge generation in the traditional automotive domains is likely to be necessary. Yet, this is a dynamic that our data cannot demonstrate.

Table 10. Technological diversification in the automotive industry in the period 1990-2014 (1 - Herfindahl index of technological classes).

Degree of technological diversification		
Year	**Based on Schmoch**	**Based on IPC4**
1990	.8764693	.9810967
1991	.876788	.9824827
1992	.8797686	.982043
1993	.8740146	.9819647
1994	.8518407	.9802363
1995	.8079252	.9756703
1996	.8161876	.9753462
1997	.8407025	.9771578
1998	.8632392	.9791559
1999	.8529423	.9774193
2000	.8539302	.9773911
2001	.8614936	.9785618
2002	.8694258	.9778602
2003	.8683141	.9782694
2004	.8633687	.9773696
2005	.8622627	.9775687
2006	.8623344	.9767273
2007	.8638501	.9761845
2008	.8661982	.9774556
2009	.8747864	.9785615
2010	.8709102	.9786994
2011	.8675669	.978252
2012	.8619233	.9781529
2013	.8504658	.97671
2014	.8540561	.9769815

Figure 5. Evolution of the technological diversification of the automotive industry in the period 1990-2014.



5.4 Change and Stability in OEMs' competitive position

The analysis of the knowledge base of the automotive industry has shown that, despite the emergence of technological opportunities in new and once-unrelated technical domains, the importance of core automotive technologies has increased over the period of analysis, confirming that powerful dynamics of change and stability animate OEMs' knowledge generation in this industry. In this paragraph, we offer evidence on the evolution of the relative position of the OEMs included in our analysis in order to assess how such dynamics of change and stability reflect into the industry composition.

To this aim, we ranked OEMs by different indicators of performance over subsequent periods, in order to assess the degree of turbulence in the industry. While frequent and marked changes in such rankings are an indication that powerful competitive dynamics are unsettling the industry, rankings that remain largely the same over time signal the persistence of a highly stable industry structure.

In order to rank OEMs, we take into account their inventive, production and financial performance. Due to data availability, the rankings cover different time-periods. Inventive performance is measured based on patent data collected from Orbit by Questel in the period 1999-2013, as patent data in 2014 might be influenced by the right truncation issue. Production performance is based on the vehicles production data collected from OICA in the period 1999-2013. Financial performance is assessed via OEMs' operating revenue and market capitalization provided by Orbis Bureau Van Dijk in the period 2010-2014.

Table 11 shows the ranking of the top 5 OEMs by inventive performance over consecutive 3-year periods. Apart from few variations, the ranking remains quite stable over time. For instance, Toyota, Honda and Nissan enter the ranking in all periods considered, with the exception of Nissan that leaves the ranking in the last period of analysis (2011-2013). In such period, we also observe the entry by Geely, which represents one of the few notable change in this first set of rankings. In fact, this OEM is not only a relatively new player in the industry but is also part of the group of Chinese carmakers that stepped into the automotive global market after the falling "iron curtain" (Schultze et al., 2015).

Table 12 displays the ranking of the top 5 OEMs by the production of vehicles over consecutive 3-year periods. The stability of the ranking over time is even more evident for this performance indicator. Between 1999 and 2007, the top OEMs and their relative position remain largely stable with the only variation represented by the entry of Honda, which in the 2005-2007 replaces Daimler. In the last two periods we observe more variations in the position of OEMs, with the entry of Hyundai, and with Toyota taking the lead for vehicles production between 2011 and 2013.

As far as the financial indicators are concerned (*Table 13* and *14*), we considered the annual operating revenue and the market capitalization of OEMs in the industry between 2010 and 2014. The rankings based on operating revenue comprise the same 5 OEMs in all considered periods, highlighting a substantial steadiness despite some slight changes in position. As an example, while Toyota and Volkswagen register the highest operating revenue across all years, Volkswagen outperforms Toyota in 2012. As for the market capitalization, this ranking has been computed yearly (and or the period 2010-2014) due to limitations in data availability. Still, we observe that three OEMs (namely, Toyota, Honda and BMW) enter the ranking in all years, with Toyota affirming its leadership in the entire period, followed by Daimler and BMW in the last two years of our sample.

Overall, despite few changes, the substantial stability in OEMs' rankings based on different dimensions of performance seems to suggest that technological changes have not resulted in major disruptions, and that the technological capabilities that have traditionally driven success in this industry continue to play a key role in explaining firms' competitive strength. In fact, Japanese and Western incumbents that have consolidated their position after the emergence of the dominant design in the late 1920s still dominate the competitive arena and new entrants have not been able to unsettle their established positions. This is consistent with the idea that the automotive industry can be considered as a clear example of a Schumpeter Mark II context with a concentrated and rather stable population of innovators (Bergek et al., 2013).

Table 11. Ranking of the top 5 OEMs by patent production over consecutive 3-year periods (1990-2013).

Patent production by top 5 OEMs over 3-year period											
1990-1992			**1993-1995**			**1996-1998**			**1999-2001**		
OEM	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**
Toyota	7,111	25.02	Hyundai	7,977	21.14	Hyundai	10,930	24.95	Toyota	7,890	18.57
Nissan	3,510	12.35	Toyota	6,746	17.88	Toyota	7,887	10.01	Hyundai	7,235	17.03
Honda	3,194	11.24	Nissan	4,060	10.76	Honda	4,213	9.62	Honda	6,085	14.32
Mazda	2,615	9.02	Honda	3,843	10.18	Nissan	4,003	9.14	Nissan	3,613	8.50
Mitsubishi	1,737	6.11	Kia	2,506	6.64	Daimler	3,049	6.96	Volkswagen	2,975	7.0

2002-2004			**2005-2007**			**2008-2010**			**2011-2013**		
OEM	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**
Toyota	11,916	23.23	Toyota	15,455	28.62	Toyota	15,532	27.33	Toyota	16,596	22.53
Honda	7,511	14.64	Honda	7,687	14.23	Honda	8,897	15.66	Honda	7,405	10.05
Hyundai	7,196	14.03	Hyundai	6,294	11.65	GM	4,631	8.15	Hyundai	6,939	9.42
Nissan	5,382	10.49	Nissan	4,120	7.63	Hyundai	4,182	7.36	Geely	6,857	9.31
Volkswagen	2,969	5.79	GM	3,413	6.32	Nissan	3,797	6.68	GM	4,714	6.4

Table 12. Ranking of the top 5 OEMs by vehicle production over consecutive 3-year periods (1999-2013)*.

Vehicles production (in million) by top 5 OEMs over a three year period														
1999-2001			**2002-2004**			**2005-2007**			**2008-2010**			**2011-2013**		
OEM	**Tot**	**%**	**OEM**	**Tot**	**%**	**OEM**	**Tot**	**%**	**OEM**	**Tot**	**%**	**OEM**	**Tot**	**%**
GM	24,136,936	14.12	GM	24,578,368	13.35	GM	27,412,978	13.10	Toyota	25,029,570	11.91	Toyota	28,479,600	11.31
Ford	20,637,442	12.07	Ford	19,939,612	10.83	Toyota	23,909,014	11.43	GM	23,218,048	11.05	GM	27,946,007	11.10
Toyota	17,471,691	10.22	Toyota	19,681,467	10.69	Ford	19,252,099	9.20	Volkswagen	19,845,687	9.44	Volkswagen	27,159,544	10.79
Volkswagen	14,999,731	8.77	Volkswagen	15,136,950	8.22	Volkswagen	17,163,907	8.20	Ford	15,080,425	7.18	Hyundai	20,976,351	8.33
Daimler	13,859,132	8.11	Daimler	13,315,811	7.23	Honda	11,017,492	5.27	Hyundai	13,187,831	7.18	Ford	17,189,540	6.83

*Data extracted from OICA and available from 1999.

Table 13. Ranking of the top 5 OEMs by operating revenues (2010-2014)*.

Yearly operating revenue (turnover million USD) of top 5 OEMs between 2010-2014									
2010		**2011**		**2012**		**2013**		**2014**	
OEM	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**
Toyota	228,481	Toyota	226,216	Volkswagen	262,527	Volkswagen	280,191	Volkswagen	253,890
Volkswagen	175,264	Volkswagen	213,554	Toyota	234,351	Toyota	249,799	Toyota	226,746
GM	135,592	GM	150,276	Daimler	152,630	Daimler	164,754	Daimler	159,736
Daimler	131,796	Daimler	139,490	GM	152,256	GM	155,427	GM	155,929
Ford	128,954	Ford	135,605	Ford	133,559	Ford	146,917	Ford	144,077

*Orbis data available from 2010.

Table 14. Ranking of the top 5 OEMs by market capitalization (2010-2014)*.

Yearly market capitalization (million USD) of top 5 OEMs between 2010-2014									
2010		**2011**		**2012**		**2013**		**2014**	
OEM	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**
Toyota	138,948	Toyota	149,839	Toyota	177,984	Toyota	195,313	Toyota	238,556
Daimler	72,255	Honda	69,348	Honda	68,397	Daimler	92,856	Daimler	90,294
Honda	68,094	Nissan	48,481	Daimler	58,280	BMW	70,750	BMW	65,611
GM	55,290	Daimler	46,560	BMW	57,926	Honda	64,003	Ford	59,654
BMW	47,362	BMW	40,316	Ford	48,473	Ford	59,769	Honda	58,862

*Orbis data available from 2010.

6. Discussion and conclusions

This study provides an overview of the knowledge base of the global automotive industry in the period of 1990-2014. In particular, we analyzed the innovation activity of the top 25 OEMs operating in the industry by reconstructing and exploring their patent portfolio.

The analysis showed that the technologies characterized by the highest patenting intensity are still related to the mechanical engineering domain, which has characterized this sector since its inception (Schultze et al., 2015). This finding suggests that although the automotive industry is currently facing an era of turmoil, its technological core –observed via the analysis of the "established" automotive technologies- still plays a dominant role in the knowledge base of the industry. However, other domains, mostly related to the electrical and digital components of the product, are gaining notable importance as documented by the trend in "high opportunity" technologies, particularly in the last 10 to 15 years of our analysis.

These findings confirm the co-existence of stability and change that, according to previous studies (e.g., Bergek et al., 2013; Schultze et al., 2015), permeates the industry's knowledge generation, offering for the first time systematic and comprehensive evidence in support of this idea. Our results also seem to indicate that both *persistence* in established technological fields and *experimentation* in new technical fields are relevant for incumbents' survival (Bergek et al., 2013), as highlighted by the substantial stability of the ranking of OEMs along different dimensions of performance. Persistent innovation in core technological fields has produced significant developments between 1990 and 2013 in the dominant regime of internal combustion engines through the use of direct injection, advanced valve systems and adoption of different materials as aluminum (Dijk and Yarime, 2010). In the development of these steady state innovations, incumbents highly benefit from scale and learning economies through the exploitation of their core competences. At the same time, the experimentation with alternative power trains and electrical domains is leading the industry's technological evolution. In fact, the technological paradigm related to the electric propulsion of automobiles has been driving the sector in the late years of our sample possibly due to increasingly stringent regulations on gas emissions and large expected volumes of sales. Consistent with studies on emerging technological trends related to the autonomous vehicles (AV) and battery electrical vehicles (BEV), which have stressed the diversified set of domains that interact and that are combined in these type of vehicles (i.e. surround sensing, localization, perception, reasoning and decision-making, motion control, telematics, and communications) (Meng et al., 2019; Borgstedt et al., 2017), our findings provide evidence of OEMs' investment into a large and varied group of "high opportunity" technologies.

To cope with a changing and increasingly pressing global regulatory framework, vehicles manufacturers have developed new capabilities in electrical components, hybrid-electric and fuel cell vehicles. As an example, hybrid car development requires the need to acquire knowledge from many fields related for instance to batteries, power electronics and electronic control systems that need to be integrated into the classical power-train architecture. This process calls for the development of new competences into electrical related fields but above all requires the capability to integrate this new knowledge into the established domains of OEMs competences through a process of knowledge reconfiguration (Geels, 2002). New and once-unrelated fields have increasingly become relevant in the industry with the consequence that OEMs have had to embrace a wider pool of technological knowledge. To solve part of the uncertainty related to electrification, many carmakers are also promoting the use of partnership and of joint platforms as for example the Volkswagen's Modular Electric Toolkit (MEB) platform[12]. Huth et al., (2013) also acknowledge that OEM are increasingly using joint ventures with electrical and chemical specialist in order to build competences within the battery value chain while maintaining its control as full integrator. In 2019 the European Commission has in fact approved the establishment of many joint ventures both between OEMs and supplier (e.g. Toyota and Panasonic operating in the R&D, manufacture and sale of prismatic automotive batteries) as well as between OEMs only (e.g. Daimler and Geely operating in the manufacturing of BEV in China)[13]. Borgstedt et al. (2016) also document the increasing importance of innovation networks (defined as forms of inter-organizational coordination) through the analysis of co-assignment instances in patent data.

In the automotive context is essential to generate knowledge in new field and to govern the competitive relations with other firms in the business ecosystem. As pointed out by prior studies (Brusoni et al., 2001; Jacobides et al., 2016; Trombini and Zirpoli, 2013), OEMs' need to master a wider range of technological domains not only to stay abreast of technological advances but also for competitive reasons aimed at governing business relations with suppliers or other types of collaborators.

Our findings also advocate that the transition will not be "competence-destroying" since established competences and classical attributes of products remain highly important in the

[12] https://www.volkswagenag.com/en/news/stories/2019/01/volkswagen-offers-electric-cooperations.html
[13] http://competitionlawblog.kluwercompetitionlaw.com/2019/11/22/automotive-industry-is-moving-towards-electrification-via-joint-ventures/

industry. A new dominant design replacing the internal combustion regime might emerge, but it is likely that OEMs will manage technological discontinuities through transition technologies that will be used to build bridges between the old and new competences required (Hekkert and van den Hoed, 2004).

As a consequence, in spite of many substantial technological modifications in the knowledge base, the industry does not seem subject to major disruptions, as incumbents still hold strong positions and no significant new entrant has challenged their dominant innovative position (Bergek et al., 2013). In fact, when looking at the composition over time of the industry we observe that a small group of company rank among the top OEMs both in the production of patent and vehicles as well as for the financial performance indicators

Overall, to solve the tension between persistent innovation, along established and continuous paths, and discontinuous innovation, along unfamiliar trajectories, incumbents need to develop ambidextrous capabilities (Tushman and O'Reilly, 1996). Although new entrants may be at an advantage position, being agile in experimenting with promising technologies, they have also limited slack resources to deal with the high level of uncertainty and failures linked to experimentation. Moreover, they lack a number of key assets and capabilities that, over time, have sheltered OEMs from external competitive attacks, including system-integration capabilities, control of key suppliers and dealers, along with the brand reputation that is necessary to serve as "*guarantors of quality*" (Jacobides et al., 2016: 1944) in the sector.

This study is not without limitations. Although we focus on the industry dynamics, a firm level analysis would enable to explore individual OEM's heterogeneity and technological trajectories by highlighting interesting deviance from the industry values. Along this line, future works should explore whether and how the competences of suppliers' and of other actors of the broader industry ecosystem are integrated into the distributed innovation model of the industry facilitating the access to new and diversified technological domains. In this respect, OEMs face the dilemma about whether and how accumulate in-house knowledge versus the knowledge they can outsource from specialists outside their boundaries.

Well-known caveats related to patent data also apply to this study. The use of patent data as a measure of innovation and firms' technological knowledge limits our possibility to trace technological evolution over time. In particular, we trace innovation and technological change only under the condition that a patent family has been granted. This confines our ability to identify knowledge accumulation in fields in which OEMs struggle to obtain patent protection. More generally, the innovation activity of an industry is not entirely revealed in patent families since many inventions never reach the market or are patented. Moreover, patents are often used for strategic purposes with the consequence that firms usually have different propensity to patent depending on their strategies for protecting their inventions. The automotive industry is however characterized by a high propensity to patent, mitigating the concerns related to the use of patent data as a way to capture innovation and emergence of technological fields in this industry (Cohen et al., 2000). In this study we also focus on the evolution of the knowledge base of the industry as proxy by the knowledge embedded in patent families disregarding, the analysis of the non-patent references. Non patent reference (NPR) refers to the citations made by patents to scientific publications or documents and is commonly considered a proxy of the scientific foundation of inventions (Trajtenberg et al., 1997). The role of scientific knowledge through for example industry-academic collaboration represents an important bridge for the generation of new technological knowledge and advancement (Cassiman et al., 2008). In parallel with the evolution of the technologies of the automotive industry, it is also reasonable to assume a change in the citations trends of NPR calling future works in the exploration of this interesting dimension.

References

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. Journal of Political Economy, 124(1), 1-51.

Alcácer, J., & Zhao, M. (2012). Local R&D strategies and multilocation firms: The role of internal linkages. Management Science, 58(4), 734-753.

Antonelli, C., & Calderini, M. (2008). The governance of knowledge compositeness and technological performance: the case of the automotive industry in Europe. Economics of Innovation and New Technology, 17(1-2), 23-41.

Becker, M., & Zirpoli, F. (2005). Knowledge–and task–partitioning in the automotive industry: coordination, governance and learning in new product development in the automotive industry.

Becker, M. C., Salvatore, P., and Zirpoli, F. (2005). The impact of virtual simulation tools on problem-solving and new product development organization. Research Policy, 34(9), 1305-1321.

Bergek, A., Berggren, C., Magnusson, T., & Hobday, M. (2013). Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation?. Research Policy, 42(6-7), 1210-1224.

Bergek, A., & Onufrey, K. (2013). Is one path enough? Multiple paths and path interaction as an extension of path dependency theory. Industrial and Corporate Change, 23(5), 1261-1297.

Borgstedt, P., Neyer, B., & Schewe, G. (2017). Paving the road to electric vehicles–A patent analysis of the automotive supply industry. Journal of cleaner production, 167, 75-87.

Borgstedt, P., Kirschke, F., Neyer, B., & Schewe, G. (2016, September). The impact of competing powertrain technologies on the formation of automotive innovation networks. In *2016 Portland International Conference on Management of Engineering and Technology (PICMET)* (pp. 2141-2151). IEEE.

Branstetter, L. G., Drev, M., & Kwon, N. (2019). Get with the program: Software-driven innovation in traditional manufacturing. *Management Science*, *65*(2), 541-558.

Braun, F. G., Hooper, E., Wand, R., & Zloczysti, P. (2011). Holding a candle to innovation in concentrating solar power technologies: A study drawing on patent data. Energy Policy, 39(5), 2441-2456.

Brusoni S, Principe A, Pavitt K. 2001. Knowledge specialization, organizational coupling, and the boundaries of the firm. *Administrative Science Quarterly* 46(4): 597-621

Cassiman, B., Veugelers, R., & Zuniga, P. (2008). In search of performance effects of (in) direct industry science links. *Industrial and Corporate Change*, *17*(4), 611-646.

Cecere, G., Corrocher, N., Gossart, C., & Ozman, M. (2014). Technological pervasiveness and variety of innovators in Green ICT: A patent-based analysis. Research Policy, 43(10), 1827-1839.

Clark, K. B., Chew, W. B., Fujimoto, T., Meyer, J., & Scherer, F. M. (1987). Product development in the world auto industry. *Brookings Papers on Economic Activity*, 1987(3), 729-781.

Cohen, W. M., Nelson, R. R., & Walsh, J. P. (2000). Protecting their intellectual assets: Appropriability conditions and why US manufacturing firms patent (or not) (No. w7552). National Bureau of Economic Research.

De Mello, A. M., Marx, R., & Souza, A. (2013). Exploring scenarios for the possibility of developing design and production competencies of electrical vehicles in Brazil. *International journal of automotive technology and management*, *13*(3), 289-314.

Dechezleprêtre, A., Neumayer, E., & Perkins, R. (2015). Environmental regulation and the cross-border diffusion of new technology: Evidence from automobile patents. *Research Policy*, *44*(1), 244-257.

De Rassenfosse, G., Dernis, H., Guellec, D., Picci, L., & de la Potterie, B. V. P. (2013). The worldwide count of priority patents: A new indicator of inventive activity. Research Policy, 42(3), 720-737.

Dijk, M., & Yarime, M. (2010). The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand. Technological Forecasting and Social Change, 77(8), 1371-1390.

Ernst, H. (1997). The use of patent data for technological forecasting: the diffusion of CNC-technology in the machine tool industry. *Small business economics*, *9*(4), 361-381.

Fine, C.H. (1998), Clockspeed: winning industry control in the age of temporary advantage, Perseus Books: Cambridge: MA.

Flamand, M. (2016). Studying strategic choices of carmakers in the development of energy storage solutions: a patent analysis. *International Journal of Automotive Technology and Management*, *16*(2), 169-192.

Fleming, L., & Sorenson, O. (2001). Technology as a complex adaptive system: evidence from patent data. *Research policy*, *30*(7), 1019-1039.

Gambardella, A., Torrisi, S., 1998. Does technological convergence imply conver- gence in markets? Evidence from the electronics industry. Research Policy, 27 (5), 445–463.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research policy, 31(8-9), 1257-1274.

Golembiewski, B., vom Stein, N., Sick, N., & Wiemhöfer, H. D. (2015). Identifying trends in battery technologies with regard to electric mobility: evidence from patenting activities along and across the battery value chain. *Journal of Cleaner Production*, *87*, 800-810.

Griliches, Z., (1990). Patent statistics as economic indicators: a survey. Journal of Economic Literature 28, 4, 1661-1707.

Hall, B. H., & Ziedonis, R. H. (2001). The patent paradox revisited: an empirical study of patenting in the US semiconductor industry, 1979-1995. *rand Journal of Economics*, 101-128.

Hekkert, M., & Van den Hoed, R. (2004). Competing Technologies and the Struggle towards a New Dominant Design. Greener Management International, (47).

Huth, C., Wittek, K., & Spengler, T. S. (2013). OEM strategies for vertical integration in the battery value chain. *International Journal of Automotive Technology and Management*, *13*(1), 75-92.

Jacobides, M. G., MacDuffie, J. P., & Tae, C. J. (2016). Agency, structure, and the dominance of OEMs: Change and stability in the automotive sector. Strategic Management Journal, 37(9), 1942-1967.

Klepper, S. (2002). The capabilities of new firms and the evolution of the US automobile industry. Industrial and Corporate Change, 11(4), 645-666.

Lee, J., & Berente, N. (2012). Digital innovation and the division of innovative labor: Digital controls in the automotive industry. Organization Science, 23(5), 1428-1447.

MacDuffie, J.P. (2013), Modularity-as-property, modularization-as-process, and modularity-as-frame: Lessons from product architecture initiatives in the global automotive industry. Global Strategy Journal, 3(1), 8-40.

MacDuffie, J. P. and T. Fujimoto (2010), 'Why dinosaurs will keep ruling the auto industry', *Harvard Business Review*, 88(6), 23–25.

Magnusson, T., & Berggren, C. (2011). Entering an era of ferment–radical vs incrementalist strategies in automotive power train development. Technology Analysis & Strategic Management, 23(3), 313-330.

Malerba, F. & Orsenigo, L. (1996). Schumpeterian patterns of innovation are technology specific, Research Policy 25(3), 451–478.

Martínez, C. (2010). Patent families: When do different definitions really matter?. Scientometrics, 86(1), 39-63.

Maxton, G. and Wormald, J. (2004), Time for a model change: Re-engineering the global automotive industry, Cambridge, Cambridge University Press.

Ménière, Y., Rudyk, I., Tsitsilonis, L., (2018). Patents and self-driving vehicles. The inventions behind automated driving. EPO. Epo.org/SDV

Meng, D., Li, X., Cai, Y., & Shi, J. (2019). Patterns of knowledge development and diffusion in the global autonomous vehicle technological innovation system: a patent-based analysis. *International Journal of Automotive Technology and Management*, *19*(1-2), 144-177.

Nelson, R. & S. Winter (1982), An Evolutionary Theory of Economic Change. Harvard University Press: Cambridge.

O'Donnell, B. (2017). "The future of the modern car is actually digital", https://www.vox.com/2017/5/23/15681058/digital-car-automotive-industry-software-designed-disruption [Accessed on 03/09/2020]

OECD (2009), Patent Statistics Manual, OECD, Paris.

Patel, P., & Pavitt, K. (1991). Large firms in the production of the world's technology: an important case of "non-globalisation". Journal of international business studies, 22(1), 1-21.

Rong, K., Shi, Y., Shang, T., Chen, Y., & Hao, H. (2017). Organizing business ecosystems in emerging electric vehicle industry: Structure, mechanism, and integrated configuration. *Energy Policy*, *107*, 234-247.

Saberi, B. (2018). The role of the automobile industry in the economy of developed countries. *International Robotics & Automation Journal*, *4*(3), 179-180

Schmoch (2008). Concept of a technology classification for country comparisons. Final report to the world intellectual property organisation (wipo), WIPO.

Schoenmakers, W., & Duysters, G. (2010). The technological origins of radical inventions. *Research Policy*, *39*(8), 1051-1059.

Schulze, A., Paul MacDuffie, J., & Täube, F. A. (2015). Introduction: knowledge generation and innovation diffusion in the global automotive industry—change and stability during turbulent times. *Industrial and Corporate Change*, 24(3), 603-611.

Schumpeter, J. (1942). Creative destruction. Capitalism, socialism and democracy, 825, 82-85.

Takeishi, A. (2002) 'Knowledge partitioning in the inter-firm division of labor: the case of automotive product development', *Organization Science*, Vol. 13, No. 3, pp.321–338.

Takeishi, A., & Fujimoto, T. (2003). Modularization in the car industry: interlinked multiple hierarchies of product, production, and supplier systems. *The business of systems integration*, 254-278.

Trajtenberg, M., Henderson, R., & Jaffe, A. (1997). University versus corporate patents: A window on the basicness of invention. Economics of Innovation and new technology, 5(1), 19-50.

Trombini, G., & Zirpoli, F. (2013). Innovation processes in the car industry: new challenges for management and research. *Automotive in Transition: Challenges for Strategy and Policy, Edizioni Ca'Foscari, Digital Publishing, Venezia*, 19-35.

Tseng, F. M., Hsieh, C. H., Peng, Y. N., & Chu, Y. W. (2011). Using patent data to analyze trends and the technological strategies of the amorphous silicon thin-film solar cell industry. Technological Forecasting and Social Change, 78(2), 332-345.

Tushman, M. L., & O'Reilly III, C. A. (1996). Ambidextrous organizations: Managing evolutionary and revolutionary change. *California management review*, *38*(4), 8-29.

UNIDO (2019). INDISTAT 2, ISIC Revision 3 Database.

Whitford, J. (2005). The new old economy: Networks, institutions, and the organizational transformation of American manufacturing. Oxford University Press.

Zirpoli, F., & Becker, M. C. (2011). The limits of design and engineering outsourcing: performance integration and the unfulfilled promises of modularity. R&D Management, 41(1), 21-43.

Zirpoli, F., & Camuffo, A. (2009). Product architecture, inter-firm vertical coordination and knowledge partitioning in the auto industry. European Management Review, 6(4), 250-264.