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Technology evolution in the global automotive industry: a patent-based analysis

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Technology evolution in the global automotive industry: a patent-based analysis[*]

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Abstract. This study explores the evolution of the knowledge base of the automotive industry. Over the last decades, the knowledge base of this industry has experienced major changes. New and originally unrelated fields have increasingly become relevant in the industry. Using data on utility patent families granted in the period 1990-2014, we map the knowledge base of the automotive industry by reconstructing and analyzing the innovative portfolio of the top firms operating in this industry. The analysis documents exploration in new technical fields as well as persistence in industry-specific technical areas, pointing to the relevance of core competences that might be difficult to accumulate for industry outsiders.

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

JEL Classification Numbers: L62, O34.

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1. Introduction

The automotive industry is a unique environment where complexity permeates product architectures, technology, organizational processes, as well as design and engineering activities. Cars are integral products (MacDuffie, 2013) that result from the combination of a large number of components, which incorporate different technologies and are linked to each other by interactions and interdependences (Zirpoli and Becker, 2011).

Over the last decades, the industry has experienced major technological changes, with implications on a wide range of strategic and organizational aspects. The emergence of new technological trajectories (e.g., electrification, autonomous driving, connectivity) is revolutionizing the industry knowledge base, and further expanding the range of technological fields that original equipment manufacturers (OEMs) have to master (Maxton and Wormald, 2004) to stay abreast of technological advances that could alter the competitive rules of the industry and facilitate the entry of new dominant players. The growing complexity of product development and the subsequent 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). Problem solving and innovation processes have also changed substantially, as a result of the on-going technology evolution. In fact, as the technology base that is used to design and produce complex products evolves, so does the nature of the innovation competences that have to be drawn upon to develop new products. In turn, firms have to adapt their problem-solving strategies to the characteristics of new relevant knowledge bodies (Becker and Zirpoli, 2005).

Despite these pervasive and wide-ranging changes, after the seminal studies of Klepper (2010) that report evidence on the early faces of the automotive industry, no further analysis has documented this phenomenon, and a systematic 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 technology base of the global automotive industry by reconstructing and analyzing the patent portfolios of the top 24 OEMs, over a 24-year period. We use the Orbit patent database that, contrary to public patent data sources, provides advanced tools to accurately trace firms' technological knowledge.

2. Empirical Strategy

2.1 Overall Research Design

Our research strategy is to dynamically map the knowledge base of the automotive industry by reconstructing and analyzing the patent portfolio of the top OEMs of the industry. To identify these actors, we rank the firms operating in the automotive industry according to different types of information. In particular, we collected data on firm's (1) revenues, (2) market capitalization, (3) production and (4) patents granted in the period 2011-2016. This information was drawn from a mix of data sources, i.e. Orbis Bureau Van Dijk (revenues and market capitalization), the International Organization of Motor Vehicle Manufacturers (production) and Orbit by Questel (patents). We finally retained the top 24[1] OEMs in at least one of the rankings based on revenue, capitalization, production or invention. The 24 OEMs retained, among which Toyota, Hyundai and Honda in the top three positions, represent overall 90% of the production of the industry, offering a significant representation of the innovation dynamics and trends of the automotive industry.

Extant literature has advanced that patent data enable to analyze cumulative technological development, generation and diffusion of knowledge as well as technological capabilities and activities (Patel and Pavitt, 1991). In addition, the classification codes attributed to patents allow to analyze the evolution of technologies at varying levels of detail, highlighting which technological fields are growing or declining and which firms lead the development of specific technological fields.

Building on these arguments, we use patents granted between 1990 and 2014 to map the knowledge base of the automotive industry. We collected patent level data from the Orbit database by Questel, which allows to aggregate firms' patent portfolios across the entire corporate tree of the focal firm[2]. This permits a comprehensive account of an organization's innovative output regardless of the unit that is responsible for the individual invention or of

[1] In a first step, we retained 25 OEMs. Then, because two of these firms (Hyundai and Kia) have agreed to form a single entity – the Hyundai Kia Motor Group – according to which Hyundai has owned 51% of Kia for many of the years of our analysis, we decided to consider these companies as a single entity. Conversely, we kept Chrysler and Fiat as separated entities since their merger occurred in the last year of our sample, 2014.

[2] Factset uses a variety of sources in identifying the entity structure of the parent firm. First and foremost are primary sources, namely 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.

internal conventions in patent applications. Orbit also uses a patent family approach by grouping together all the patent documents referring to the same single invention by means of common priority filing (Martinez, 2010)[3]. It is in fact an established practice for firms to seek protection in multiple countries by filing several patent applications in many patent offices (Martinez, 2010). The patent family approach has two main advantages. First, it avoids overestimating the scope of firm knowledge by consolidating multiple patent documents associated to the same invention (Alcácer and Zhao, 2012). Second, it reduces any geographical and institutional bias correlated to the specificity of the country in which protection is sought, as well as potential structural lack of information in patent documents (De Rassenfosse et al., 2013).

The dataset includes procedural information about patents families (i.e. publication, priority and application number of the patent; grant, application and priority dates of the patent) as well as complete references to the firm owning the patent family, and the invention's technological classes according to the International Patent Classification (IPC) and to the Cooperative Patent Classification (CPC).

Our final dataset comprises 416,872 patent families granted between 1990 and 2014 to the top 24 OEMs of the automotive industry. One important caveat is that our data are right-censored. In collecting the patent data from Orbit, we imposed a cut-off date at December 31st, 2016, but we retained in the sample only patent granted up to 2014 in order to mitigate the right-censored issue[4]. We use the priority year of the patent family to proxy the invention's date. This approach allows considering the year that is closer to the firm's actual inventive effort.

Figure 1 represents the yearly distribution of patent families between 1990 and 2014 whereas Figure 2 reports the cumulated number of families in the industry in the same period.

Table 1 reports the total number of patent families granted per year in the industry between 1990 and 2014.

[3] FamPat database provided by Orbit, groups together all the patent documents referring to the same single invention. 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 plenty of 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.

[4] As reported by Hanningan et al. 2015, the lag between the application and the grant of the patent average nearly around 3 years. The data used in this study are truncated when approaching the last years of our time window.

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Figure 1: distribution of the number of patent families by year in the automotive industry.

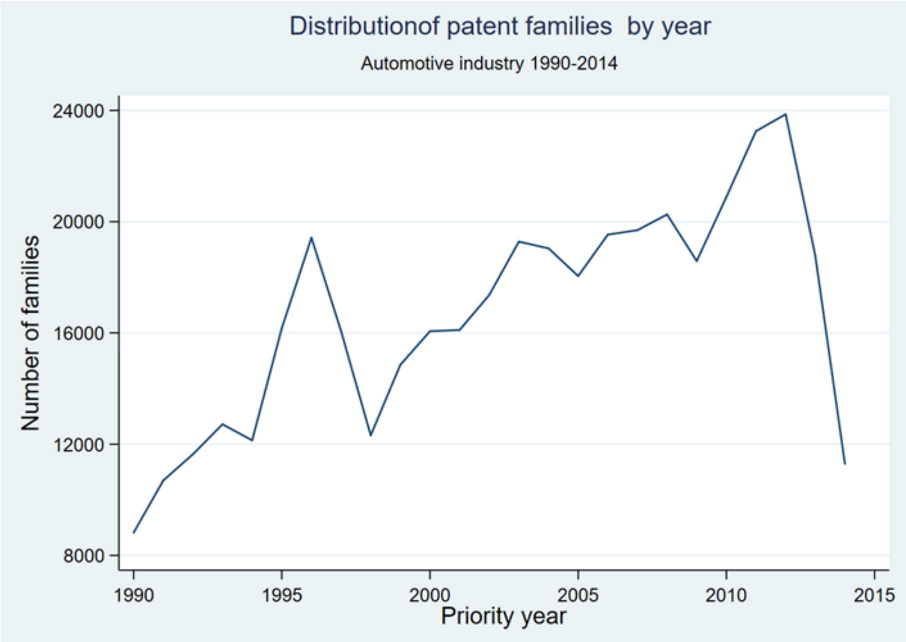


Figure 2: cumulative number of patent families in the automotive industry.

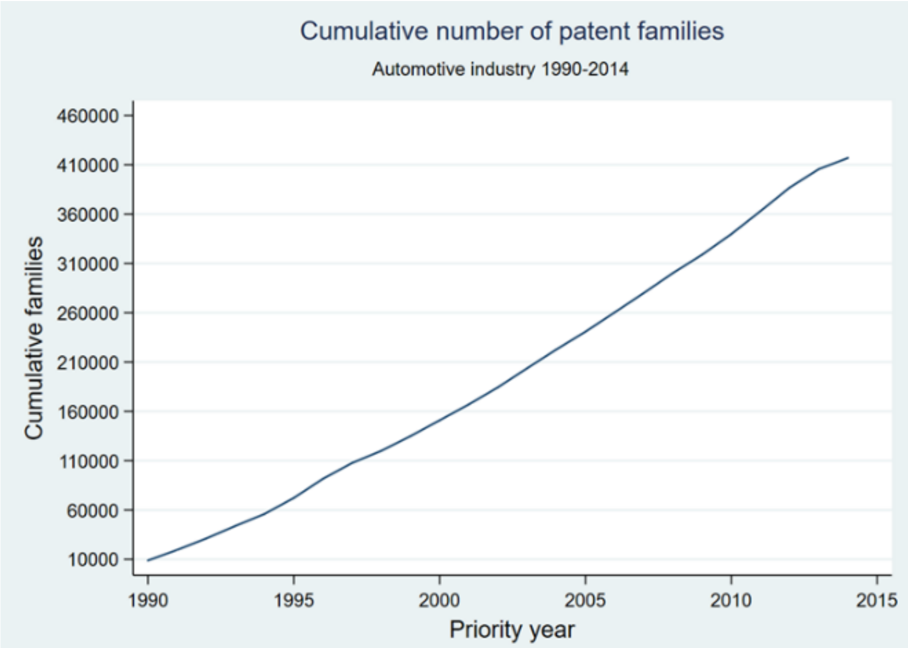


Table 1: number of patent families in the automotive industry between 1990 and 2014.

Year	**Tot. Fam.**	**% of Tot. Fam. in industry**	**Cum.**
1990	8,817	2.12	8,817
1991	10,694	2.57	19,511
1992	11,637	2.79	31,148
1993	12,715	3.05	43,863
1994	12,137	2.91	56,000
1995	16,168	3.88	72,168
1996	19,424	4.66	91,592
1997	16,063	3.85	107,655
1998	12,319	2.96	119,974
1999	14,853	3.56	134,827
2000	16,061	3.85	150,888
2001	16,106	3.86	166,994
2002	17,365	4.17	184,359
2003	19,283	4.63	203,642
2004	19,041	4.57	222,683
2005	18,045	4.33	240,728
2006	19,534	4.69	260,262
2007	19,695	4.72	279,957
2008	20,259	4.86	300,216
2009	18,584	4.46	318,800
2010	20,887	5.01	339,687
2011	23,255	5.58	362,942
2012	23,861	5.72	386,803
2013	18,778	4.50	405,581
2014	11,291	2.71	416,872
Tot.	**416,872**	100.00	

The percentage of families are computed with respected to the total number of patent families in the industry that is 416,872.

3. Results

We analyze our data at the aggregate industry level (Section 3.1). Through the industry level of analysis, we seek to reconstruct the evolution of the technological fields in which the OEMs collectively have developed new knowledge over the time period 1990-2014. In addition, we seek to identify the "established" technologies that characterize the industry knowledge base, while at the same time isolating those technologies that are gaining importance over time, which we label as "emerging" technologies. In doing so, we focus on the evolution patterns of the 35 technological fields identified using the Schmoch's classification (Schmoch, 2008)[5]. In fact, this classification identifies 35 technological fields that can be aggregated into 5 main sectors: *Electrical engineering*, *Instruments*, *Chemistry*, *Mechanical engineering*, and *Other fields* (like civil engineering). We complemented this analysis through a more disaggregated approach that analyses the trends at the IPC level, which we use specifically to identify *established* and *emerging* technologies.

3.1 Industry level analysis

3.1.1 Evolution of the technological fields in the Schmoch's classification

The majority of patent families in our dataset (62.31%) is linked to only one technological field whereas only about 25% are linked to two different technological fields according to the Schmoch's classification. Table 2 reports the number and percentage of patent families in each field of the Schmoch's classification. As expected, the *Mechanical engineering* sector of the Schmoch's classification includes the technologies that mostly characterize the automotive industry. In particular, *Transport*, covering all type of transport technologies and applications with a dominance of automotive technologies, represents 42.28% of the sample. *Engines, pumps and turbines* represents 19.05% of the sample and covers non-electrical engines for all type of applications with a dominance of automobiles applications. *Mechanical elements* (14.42%) includes all engineering elements of machines such as joints and couplings, pipe-line systems or mechanical control devices. The other sectors of the classification are not very populated. Within *Instrument*, the technology with the highest percentage of patent families granted is *Measurement* (7.85%) which covers a broad variety of different techniques and applications (e.g. measurement of mechanical properties as oscillation or speed).

[5] To identify the 35 technological fields of the Schmoch's classification we used the 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), WIPO*.

Table2: number and percentage of families in each technological field of the Schmoch's Classification 1990-2014.

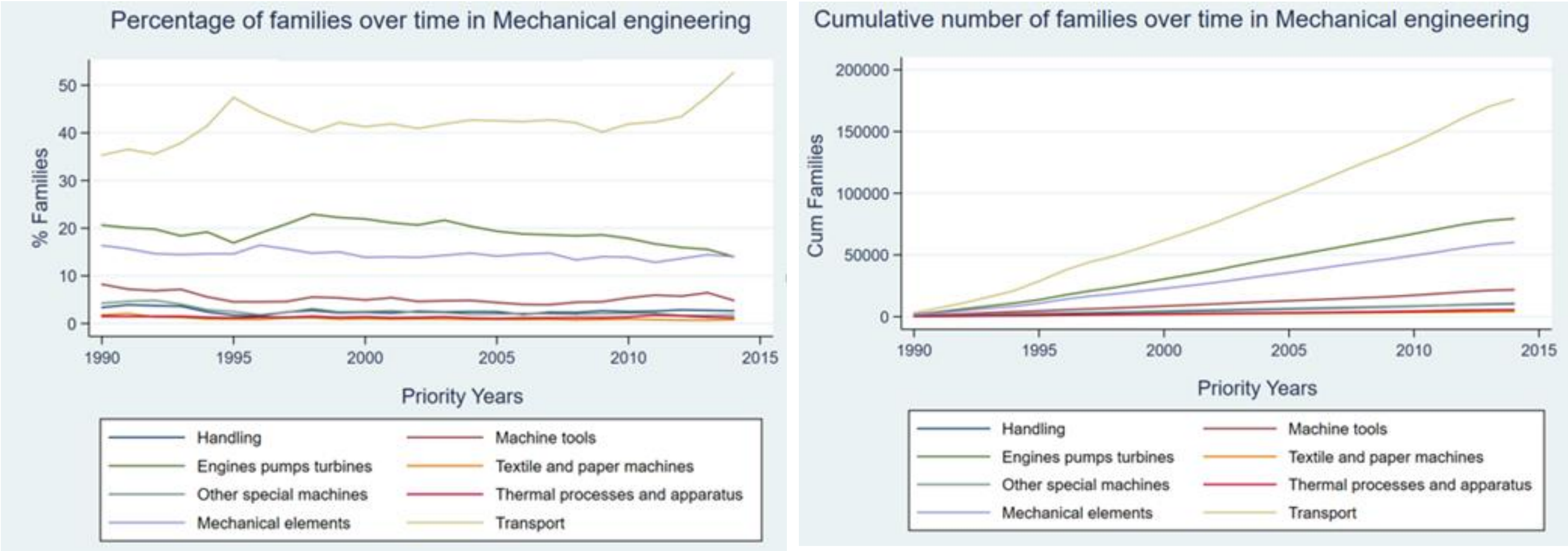
Field number	Sector description	Field description	Tot. Fam.	% of Tot. Fam. in industry
1	**Electrical engineering**	**Electrical machinery, apparatus, energy**	**48,889**	**11.73**
2	Electrical engineering	Audio-visual technology	12,290	2.95
3	Electrical engineering	Telecommunications	11,110	2.67
4	Electrical engineering	Digital communication	9,572	2.30
5	Electrical engineering	Basic communication processes	2,335	0.56
6	Electrical engineering	Computer technology	18,484	4.43
7	Electrical engineering	IT methods for management	1,953	0.47
8	Electrical engineering	Semiconductors	9,946	2.39
9	Instruments	Optics	8,182	1.96
10	**Instruments**	**Measurement**	**32,730**	**7.85**
11	Instruments	Analysis of biological materials	5,592	1.34
12	Instruments	Control	18,776	4.50
13	Instruments	Medical technology	3,692	0.89
14	Chemistry	Organic fine chemistry	3,507	0.84
15	Chemistry	Biotechnology	1,594	0.38
16	Chemistry	Pharmaceuticals	2,027	0.49
17	Chemistry	Macromolecular chemistry, polymers	4,158	1.00
18	Chemistry	Food chemistry	2,257	0.54
19	Chemistry	Basic materials chemistry	4,478	1.07
20	Chemistry	Materials, metallurgy	11,398	2.73
21	Chemistry	Surface technology, coating	10,459	2.51
22	Chemistry	Micro-structural and Nano-technology	750	0.18
23	Chemistry	Chemical engineering	13,469	3.23
24	**Chemistry**	**Environmental technology**	**21,197**	**5.08**
25	Mechanical engineering	Handling	10,550	2.53
26	**Mechanical engineering**	**Machine tools**	**21,790**	**5.23**
27	**Mechanical engineering**	**Engines, pumps, turbines**	**79,401**	**19.05**
28	Mechanical engineering	Textile and paper machines	4,051	0.97
29	Mechanical engineering	Other special machines	10,041	2.41
30	Mechanical engineering	Thermal processes and apparatus	5,592	1.34
31	**Mechanical engineering**	**Mechanical elements**	**60,101**	**14.42**
32	**Mechanical engineering**	**Transport**	**17,6250**	**42.28**
33	Other fields	Furniture, games	4,062	0.97
34	Other fields	Other consumer goods	3,264	0.78
35	**Other fields**	**Civil engineering**	**14,106**	**3.38**
Tot. number of families			**648,053**	
Tot. number of distinctive families			**416,872**	

Note that the Schmoch's classification includes 35 technological fields that are associated to 5 main technological sectors. To associate every patent family to a field in the Schmoch's classification we used the IPC concordance table provided by the WIPO (March 2018 version). As each patent family can embodies more than one IPC classes, some families are associated to multiple technological fields of the Schmoch's classification. The most representative fields in each sector are in bold. The most representative sector is Mechanical engineering with a prominent presence of fields that typically characterize the industry as for example Transport and Mechanical elements. Other sectors are not so much populated with the exception of Electrical Engineering where the field of Electrical machinery, apparatus, energy represent about 12% of the patent granted in our sample.

Within *Chemistry*, *Environmental technologies* (5.08%) is the most representative field (e.g. use and development of filters, waste disposal, gas-flow silencers, waste combustion) followed by *Control* with 4.50% of the patent families granted between 1990 and 2014 (e.g. elements for controlling and regulating electrical and non-electrical systems as for example traffic control). The *Civil engineering field*, covering in general the construction of road and buildings, represents only 3.38% of the granted patent families. Worth to note in table 3 is the *Electrical engineering* sector where *Electrical machinery, apparatus and energy* technological field ranks fourth by number of patent families in our sample, representing about the 12% of the patent families within the industry. This field covers the non-electronic part of electrical engineering as for example the generation, conversion and distribution of electric power, electric machines as well as basic electric elements such as resistors, magnets or cables.

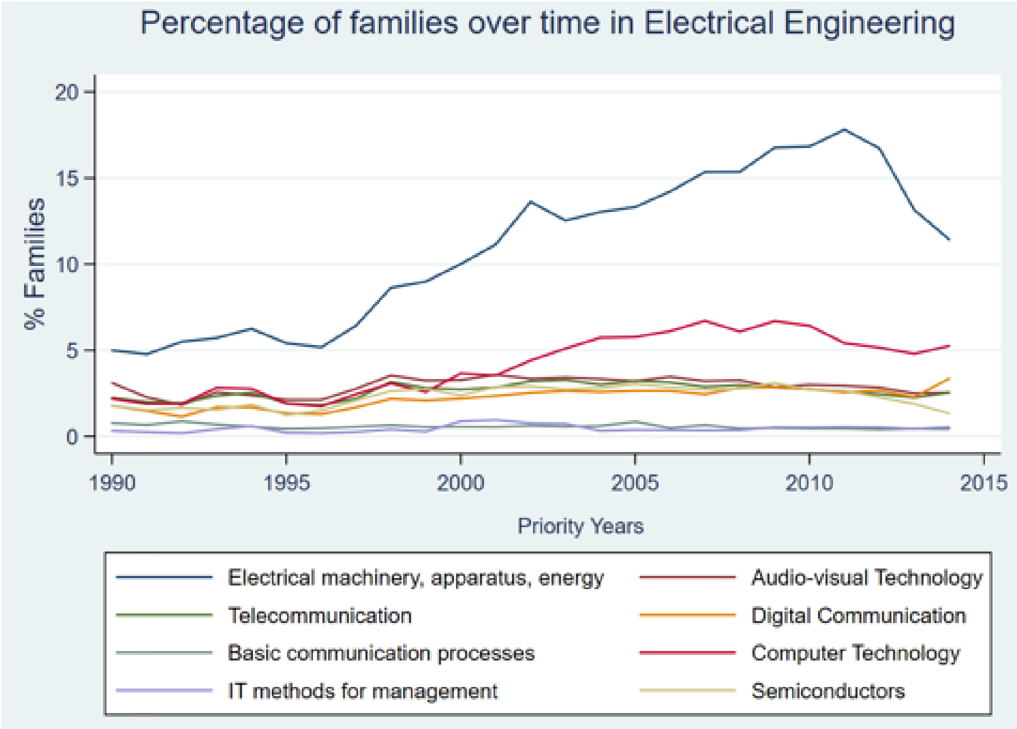
The figures below show the evolution over time of the percentage and cumulative number of families in the five *sectors* of the Schmoch's classification. The percentage is computed over the total number of families in the industry in each year between 1990 and 2014. Figure 3 displays the evolution over time of the technologies related to the sector of *Mechanical engineering*. We observe that the technologies linked to the *Transport* field drive this sector. Other important fields are *Engines, pumps and turbines* followed by the technologies related to *Mechanical elements* that show a stable trend over time. We also observe that, apart from a short period of sustained growth between 1993 and 1995, the percentage of patent families associated to *Transport* has been quite stable at around 40%, registering an increasing trend in families granted in this field only starting from 2010.

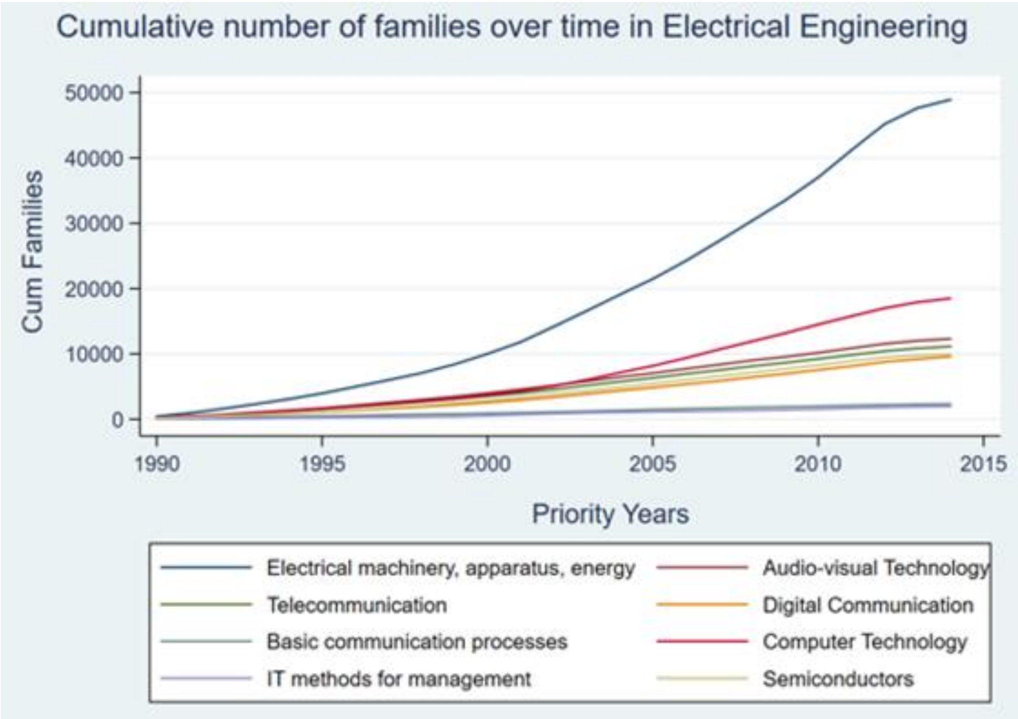
Figure 3: percentage and cumulative number of families in the sector of Mechanical engineering.



In the *Electrical engineering* sector (Figure 4), the field of *Electrical machinery, apparatus, and energy* has progressively increased approximately since 1996, showing a decreasing trend right after 2010. Compared to the other fields of the Schmoch's classification, technologies linked to the *Electrical machinery* show a sustained growth in terms of percentage of families over the period considered.

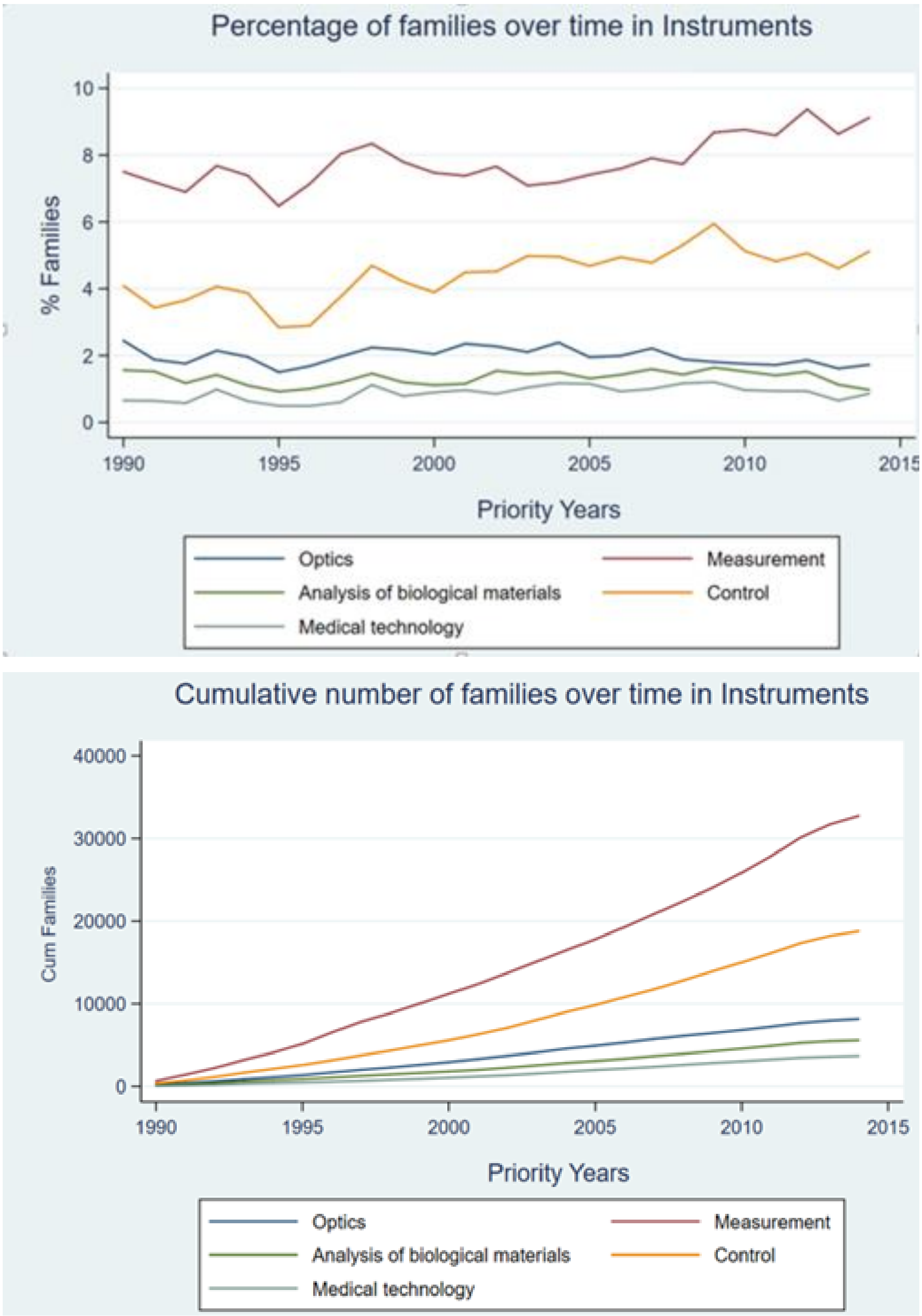
Figure 4: percentage and cumulative number of families in the sector of Electrical Engineering.





The technological fields included in the *Instrument*'s sector (Figure 5) show overall a lower percentage of families per year compared to the fields described above, like *Transport*. In this sector, we observe that the most relevant technologies are linked to the fields of *Measurement* and *Control* whereas the technologies linked to *Optics* and *Medical technologies and analysis of biological material* have overall a much lower cumulative number of families.

Figure 5: percentage and cumulative number of families in the sector of Instrument.



The technologies related to the sector of *Chemistry* (Figure 6) show a lower percentage of patent families per year. In particular, there is a decline in the patent families granted in these technologies between 1991 and 1996, which is followed by an increasing trend in the subsequent periods. The most representative technologies are related to the fields of *Environmental technologies, Chemical engineering, Metallurgy* and *Coating* that show overall similar trends over time.

Figure 6: percentage and cumulative number of families in the sector of Chemistry.

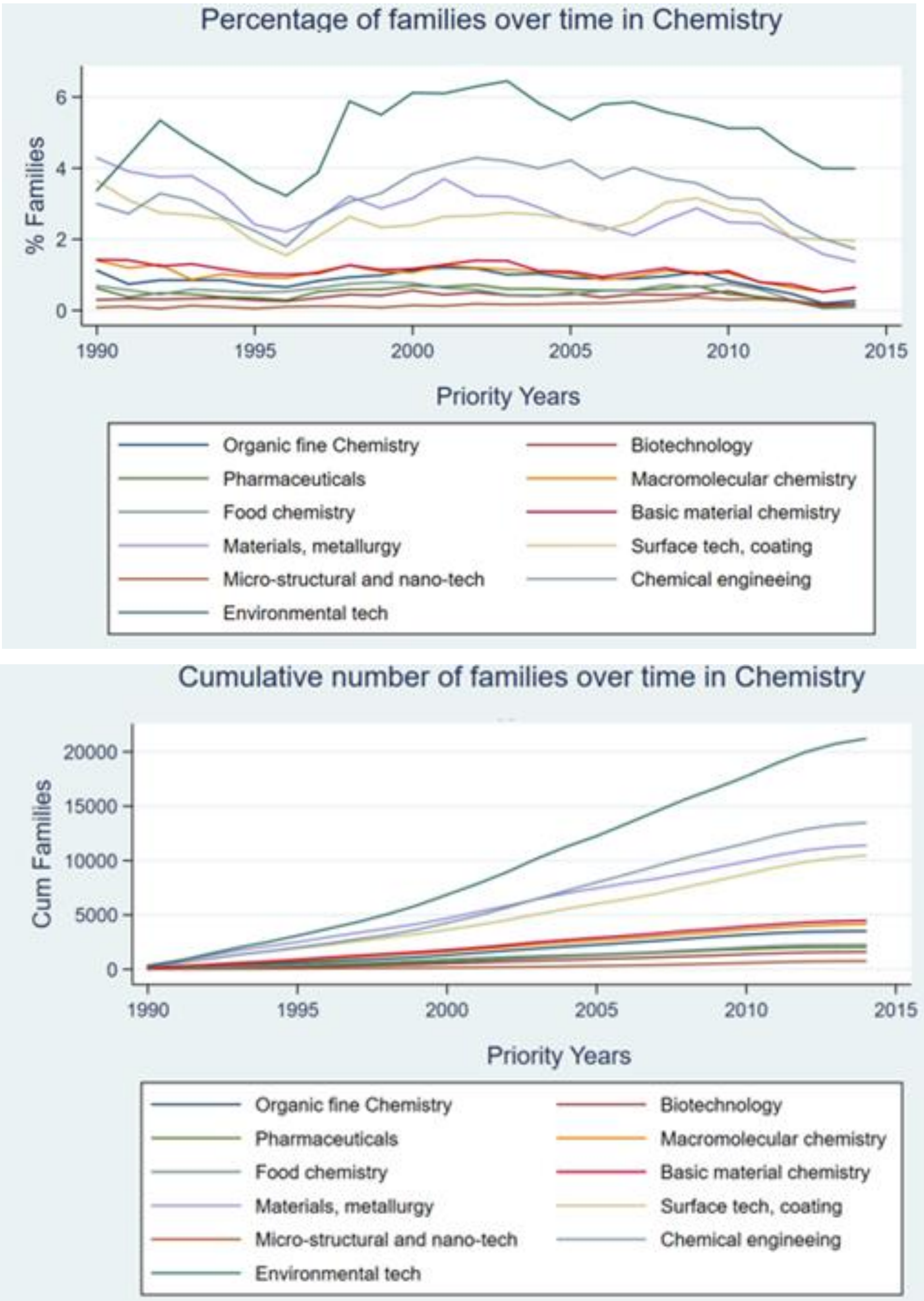
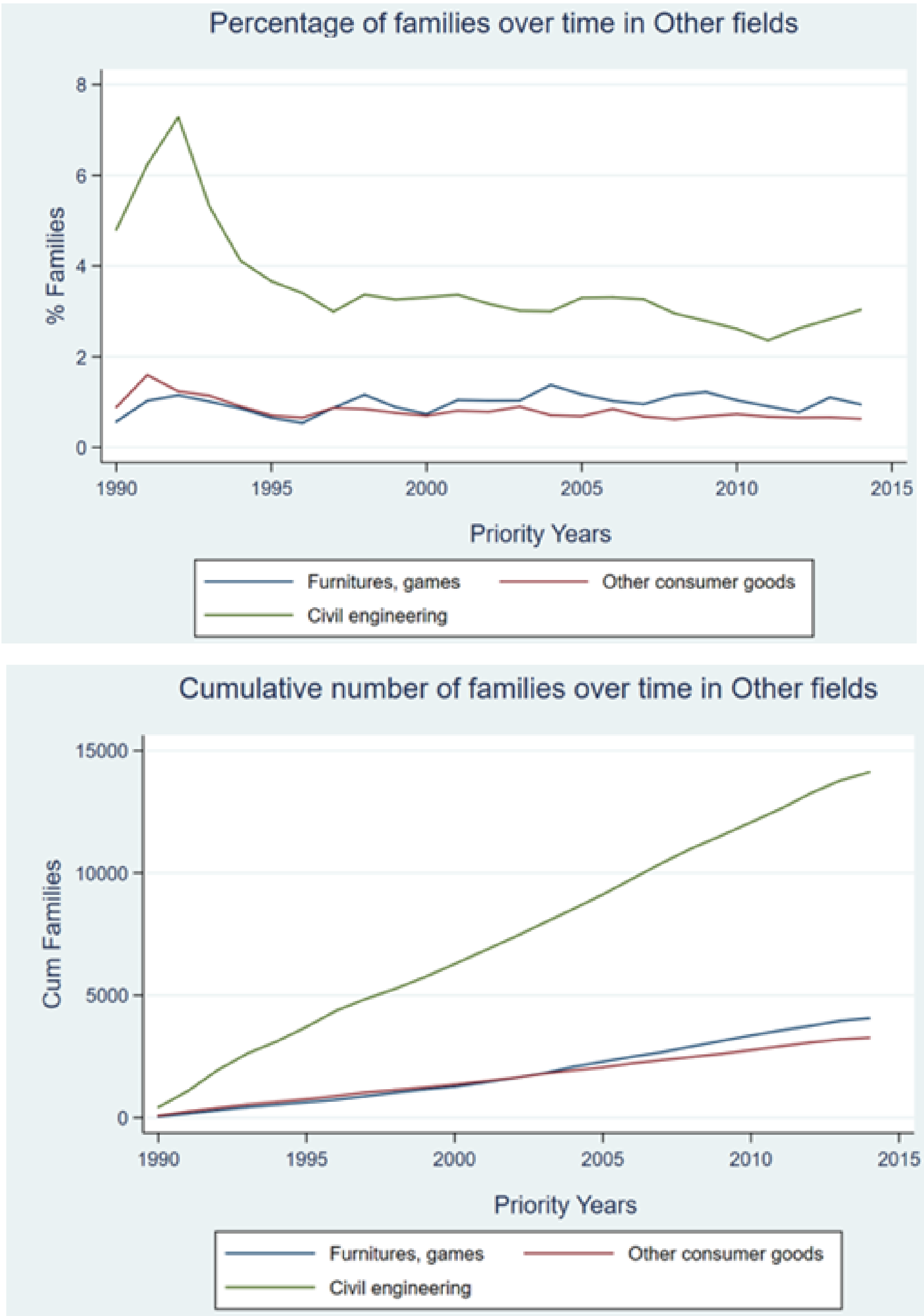


Figure 7 displays the evolution over time of technologies within the sector *Other fields*, which includes *Civil engineering*, *Furniture*, *games* and *Other consumers goods*. Apart from the *Civil engineering*, the other technologies related to *Furniture* and other *Other consumers good* show very similar trends.

Figure 7: percentage and cumulative number of families in other fields.



3.1.2 Identification of *established* and *emerging* technologies

To provide a more disaggregated view on the technological evolution in the industry, we also take into account the trends at the level of the technological classes embedded within patent families using the International Patent Classification (IPC)[6]. The dataset includes 673 distinct IPC classes (4 digit) that are cited in patent families. Most of the patent families are associated to only one IPC code (48%) with only about 39% of families associated to no more than three IPC codes. Interestingly enough, the average number of IPCs embedded in patent families tends to increase over time ranging from an average of 6 IPCs per family in 1990 to an average of above 8 IPCs per family in 2005. This is indicative of a surge in the technological complexity embedded in patent families. In line with the knowledge recombination literature (Fleming et al., 2001), this seems to suggest that there is an increase in the recombination of technical fields within the same invention, revealing a pattern of cross-fertilization between technological domains.

Table 3 reports the patenting activity in the top 20 classes representing about 64% of the sample with a total of 268,991 patent families in these technologies. As one may expect, the top 5 IPCs are in fields related to motor vehicles, gearing, propulsion and engines. In general, the most frequent IPCs are associated to the *Mechanical engineering sector* of the Schmoch's classification (as discussed in section 3.1.1). This stylized fact points to the strong engineering competences required to operate in the industry and to a persistence in the use of these technologies in patented inventions.

[6] We considered also the Cooperative Patent Classification (CPC) in the identification of established classes. CPC is an extension of the IPC classes and has been used in the identification of specific technologies flagged as established in the automotive industry according to the report from EPO 2018. In particular, the class F16D48 that includes technologies related to External control of clutches has been flagged as established relative to the 4 digits scheme F16D which includes all technologies related to couplings for transmitting rotation.

Table 3: top 20 most frequent IPC classes (IPC 4level) in the automotive industry between 1990 and 2014.

Class	Description	Tot. Fam.	% of Tot. distinctive Fam.
B60R	Vehicles, Vehicles fitting, vehicle parts	45,731	10.97
B62D	Motor vehicles, trailers	38,401	9.21
B60K	Arrangement or mounting of propulsion units or of transmission in vehicles	37,409	8.97
F02D	Controlling combustion engines	36,929	8.86
F16H	Gearing	29,353	7.04
H01M	Process or means, batteries, for conversion of chemical energy into electrical	21,393	5.13
B60W	Conjoint control	20,790	4.99
F02M	Supplying combustion engines (carburettors, fuel injection)	19,803	4.75
F02B	Internal combustion piston engines, combustion engines in general	17,793	4.27
F01N	Apparatus for internal combustion engines	16,909	4.06
B60L	Propulsion of electrically-propelled vehicles	16,022	3.84
B60J	Protective coverings specially adapted for vehicles	13,812	3.31
B60T	Vehicle brake control systems or parts thereof	13,371	3.21
G06F	Electric digital data processing	13,040	3.13
B60N	Seats specially adapted for vehicles	12,623	3.03
F16D	Couplings for transmitting rotation	10,550	2.53
H01L	Semiconductor devices	9,946	2.39
G08G	Traffic control systems	8,877	2.13
F01L	Cyclically operating valves for machines or engines	8,252	1.98
B01D	Separation	8,123	1.95
Tot patent families in top 20 IPC classes		**399,127**	
Tot distinctive patent families in top 20 IPC classes		**268,991**	
Tot distinctive patent families in the industry		**416,872**	

Note that duplicate of patent families is possible since the same patent family may be associated to multiple IPC. Also, note that all technological classes cited by each patent family are taken into account using the IPC 4level.

In this section, we aim at analyzing those technological fields that persistently characterize the sector, which we label "established" technologies, while simultaneously isolating "emerging" technologies, i.e. technologies that are relatively novel to the industry. To analyze the established technologies in our sample, we build upon on the work by Ménière et al. (2018), which leveraged the competences of the European Patent Office's examiners to identify "*all the technologies that can be found in today's mass-produced vehicles which do not include the features of connectivity and automated driving*" (p. 17). These technologies are reported in Table 4 with the indication of the total number of families and percentage of patent families in each technological class.[7]

A total of 221,964 patent families are flagged as *established* representing about 53% of the sample. Most of the innovative activity linked to established technologies relates to two broad

[7] A study by Bergek and Onufrey (2013) identifies traditional classes as those classes that have been used throughout the entire period under study.

technological areas of *Transporting* (technologies in the group B of the IPC scheme) and of *Mechanical engineering, lighting and heating* (technologies in the group F of the IPC scheme). An exception is the class H01T which represents however only 0.12% of the patent families in our sample. This class is included in the H group of the IPC classification pertaining to technologies in the electricity field.

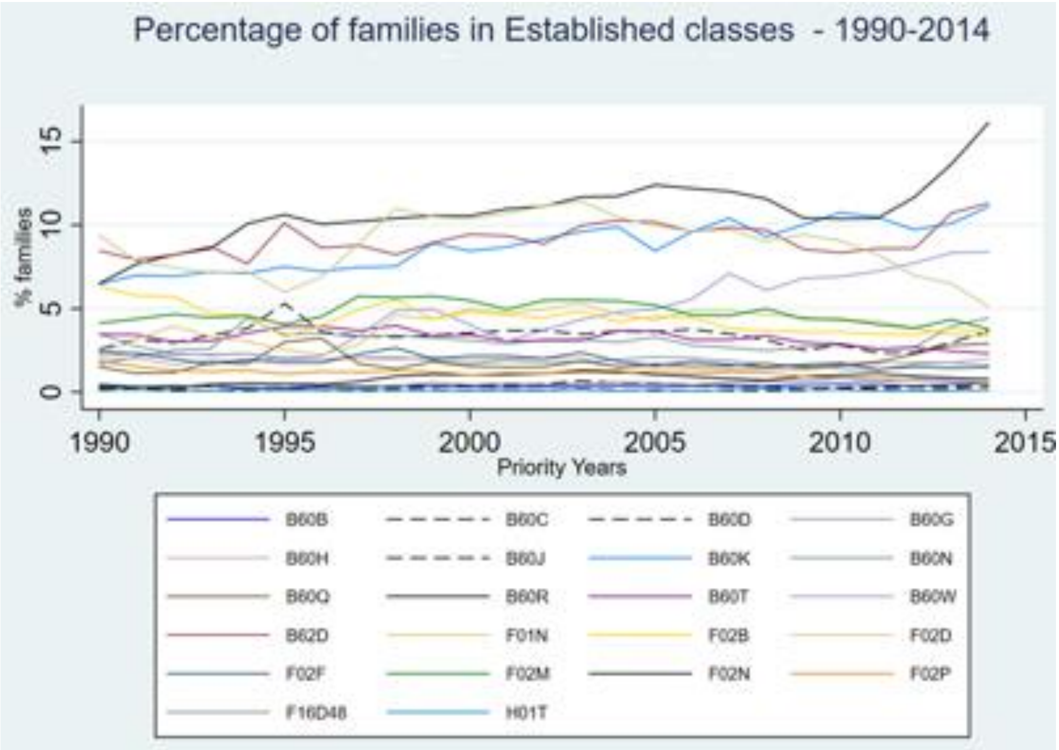
Table 4: Total number of patent families in established technological classes of the automotive industry between 1990 and 2014 as defined by Ménière et. al 2018.

Class	Description	Tot. Fam.	% of Tot distinctive Fam.
B60R	Vehicles, vehicles fitting, vehicles parts	45,731	10.97
B62D	Motor vehicles, trailers	38,401	9.21
B60K	Arrangement or mounting of propulsion units or of transmission in vehicles	37,409	8.97
F02D	Controlling combustion engines	36,929	8.86
B60W	Conjoint control	20,790	4.99
F02M	Supplying combustion engines (carburetors, fuel injection)	19,803	4.75
F02B	Internal combustion piston engines	17,793	4.27
F01N	Exhaust Apparatus (gas flow silencers)	16,909	4.06
B60J	Protective coverings specially adapted for vehicles	13,812	3.31
B60T	Vehicle brake control systems or parts thereof	13,371	3.21
B60N	Seats specially adapted for vehicles	12,623	3.03
B60G	Vehicle suspension arrangements	7,883	1.89
B60Q	Signaling and lighting	7,727	1.85
F02F	Cylinders, pistons, casings for combustion engines	7,658	1.84
B60H	Arrangement of adaptations of heating	7,287	1.75
F02P	Ignition	4,514	1.08
F02N	Starting of combustion engines	3,569	0.86
F16D48	External control of clutches	2,205	0.53
B60B	Vehicles wheels	1,496	0.36
B60C	Vehicle tyres	1,488	0.36
B60D	Vehicle connections	524	0.13
H01T	Spark gaps, overvoltage arresters using spark gaps	493	0.12
Tot patent families in *established* classes		**318,415**	
Tot distinctive patent families in *established* classes		**221,964**	
Tot distinctive patent families in the industry		**416,872**	

Note that F16D48 is the extension of the IPC level 4 classification as it includes the group "48". Following the indication of EPO 2018 for the identification of established classes, we reported the total number of families in the IPC level 6 of the class F16D48 that is 2205 compared to a total number of patent families of 10550 when this class is taken at the 4 digits level. Also, note that all technological classes cited by each patent family are taken into account.

Figure 8 shows the evolution over time of established classes displaying the percentage of patent families in these classes computed over the total number of patent families in the industry in every year. Overall, the percentage of families in these classes is quite stable over time. We also observe that of the 22 established technologies, only 5 classes have a percentage higher than 5% over time, while the other technologies remain below a 5% threshold. It is worth mentioning that the class B60R (i.e. vehicles parts and vehicles in general) shows a progressive increase over time especially in the period 2010-2014.

Figure 8: percentage of families in established technological classes.



The technologies related to B60K (i.e. arrangement of propulsion or of transmission in vehicles) and to B62D (i.e. motor vehicles) also show a progressive increase. Another class that appears to gain importance over time is B60W (i.e. conjoint control) which shows a progressive increase in the number of patent families over time with respect to the aggregate values between 2001 and 2014. This technology refers to a programmed or condition-responsive automatic controller on board of a vehicle that acts together with other units as for example propulsion or gearing system to solve a particular problem or in response to specific driving conditions.

Contrary to the above-mentioned trends, the technologies linked to the class F02D (i.e. controlling combustion engines) declines over time, in particular in the period between 2004 and 2014.

A comparison between the top 20 technological classes reported in Table 3 and the established technologies as listed in Table 4, shows that, as one may expect, the established technologies are those in which patenting activity is higher. This comparison indicates that the majority of the most representative classes in our sample have also been flagged as established technologies within the automotive industry. However, there is also a group of classes characterized by a high patenting activity but that are not considered as established (e.g. F16H, B60L, G06F). Many of these classes clearly pertains to the electrical components of vehicles as for example batteries (i.e. H01M class) or the propulsion of electrically-propelled vehicles (i.e. B60L).

In the next analysis, we consider the growth rate of patent families in technological classes in order to isolate the technologies that have gained importance over time, as proxied by their growth rate. We label these technologies as "emerging". In particular, building on Corroncher et al., (2003) we compute the growth rate of patent families in each technological class as the sum over two years in order to avoid peaks due to random factor affecting the patenting procedure. To be identified as emerging, the growth rate of the class has to be above the average of the sample, including all technologies, for at least 3 consecutive periods. As an additional criterion, emerging classes should not represent more than 3% of the overall sample of patent families in the periods in which their growth rate is above the average of the sample. Using these two criteria, we identified 55 technologies whose importance has grown over time. The average growth rate of the entire sample in the time window 1990-2014 is 19%. Emerging technologies have an average growth rate of 26% compared to an average growth rate of 18% of non-emerging technologies computed over the entire period of our sample (1990-2014).[8] Table 5 reports the first 20 classes[9] identified as emerging through this approach with the indication of the total number of families in each class computed with respect to the total sample.

[8] The same approach has been replicated using by computing the growth rate over years instead as the sum over two periods as well as using different cut off level as for example 3 and 5 consecutive years of growth as well as 3% and 5% as the percentage of the families in the sample. The total number of families identified may slightly changes but the top classes identified remains quite stable across the use of these different cut off levels.

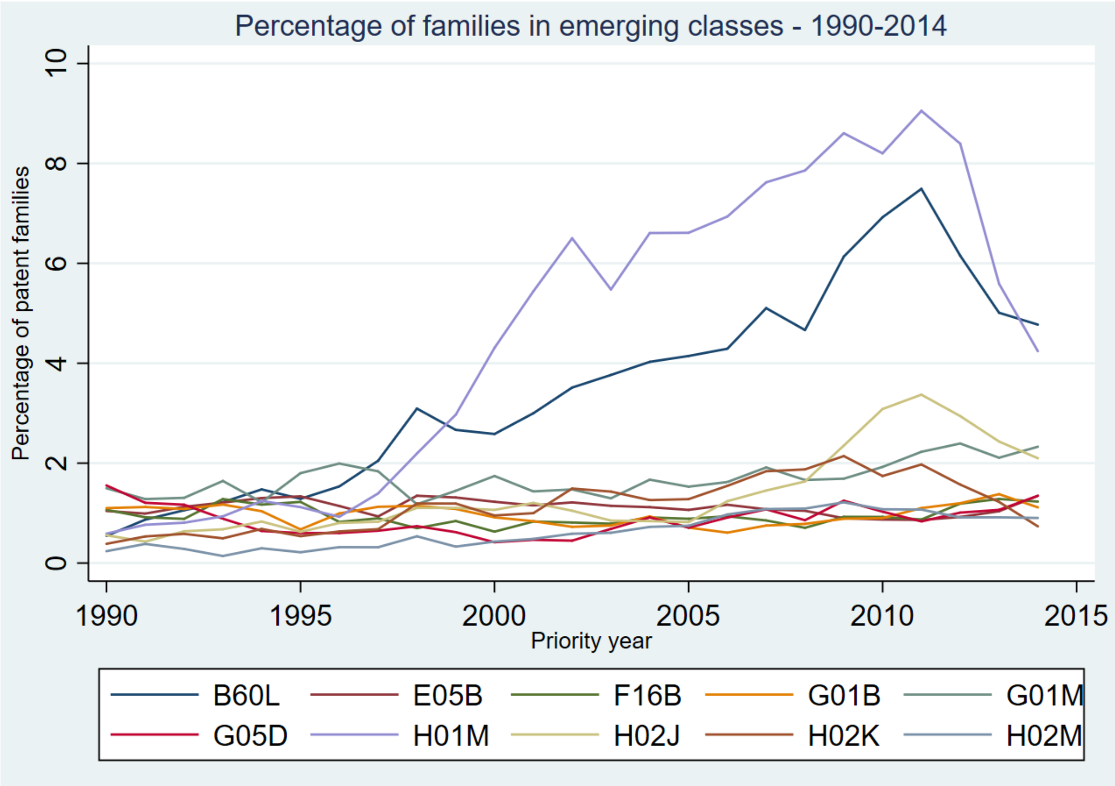
[9] The full list of classes identified using this approach is reported in appendix A.

Table 5: total number of patent families in the first 20 emerging technologies between 1990 and 2014 sorted by the overall number of families in the sample.

Class	**Description**	**Tot. Fam.**	**% of Tot. distinctive Fam.**
H01M	Process or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	21,395	5.13
B60L	Propulsion of electrically-propelled vehicles	16,023	3.84
B60Q	Arrangement of signaling or lighting devices	7,727	1.85
G01M	Testing static or dynamic balance of machines or structures	7,217	1.73
H02J	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy	6,185	1.48
H02K	Dynamo-electric machines	5,221	1.25
E05B	Locks; accessories therefor; handcuffs	4,579	1.10
G01B	Measuring length	3,968	0.95
F16B	Devices for fastening or securing constructional elements or machine parts together	3,901	0.94
F02N	Starting of combustion engines	3,569	0.86
G05D	Systems for controlling or regulating non-electric variables	3,546	0.85
H04B	Transmission	2,916	0.70
H02M	Apparatus for conversion between ac and ac, between ac and dc	2,867	0.69
E05F	Devices for moving wings into open or closed position	2,481	0.60
C01B	Non-metallic elements; compounds thereof	2,335	0.56
G06Q	Data processing systems or methods	1,964	0.47
G08B	Signaling or calling systems	1,592	0.38
H02G	Installation of electric cables or lines	1,563	0.37
F25B	Refrigeration machines	1,492	0.36
B60C	Vehicle tires	1,488	0.36
Total patent families flagged as *emerging*		**102,029**	
Total distinctive patent families in the industry		**416,872**	

Figure 9 exhibits the percentages of patent families in the top 10 emerging classes (by total number of families between 1990 and 2014). The percentages are computed yearly over the total number of families in the industry in the focal year. Again, the technologies related to the electric vehicle stand out. For instance, the class H01M (i.e. technologies related to the conversion of the chemical energy into electrical) shows a sustained increase in the percentage of patent families starting from the late 90s'. Also, class B60L (i.e. propulsion of electrically propelled vehicles) shows a progressive increase starting from 2000.

Figure 9: percentage of patent families in emerging classes computed over the total number of patent families in the industry in every year.



3.3 Technological diversification in the industry

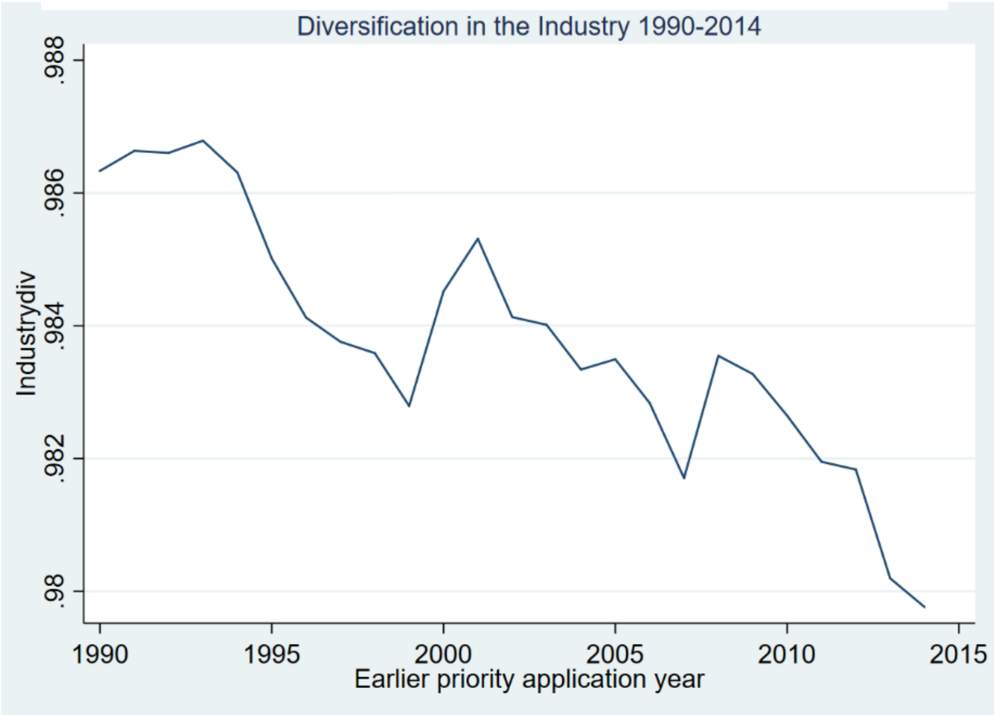
In this section, we take into account the technological diversification computed both at the industry and at the firm level. The technological diversification is computed using the Herfindahl Index over both the IPC and the Schmoch's classification. The Herfindahl index measures the degree of concentration of patent families across technological classes. It takes the value 1 if patent families are associated to a single class only, and approaches 0 if the families are evenly dispersed over a large number of technological fields. This variable is a more accurate measurement of technological diversification than a simple count of technologies in a firm's knowledge base, since the latter is very sensitive to accidental discoveries in particular technology fields. We transform the Herfindahl index into a measure of diversification by taking 1-HHI in order to interpret higher values of the index as higher levels of diversification. Table 10 reports the yearly diversification values of the automotive industry computed both on the IPCs as well as on the Schmoch's classification level. It is possible to observe that the level of industry diversification tends to decrease slightly over time. The decline of technological diversification is more evident when the index is computed using aggregated set of technologies from the Schmoch's classification (second column of Table 10). We note that the diversification declines from 0.9 in 1990 to 0.8 in 2014. Over time, between 1994 and 1995, the diversification level also reaches the bottom values of 0.84 as in 2014. The declining trend in diversification is less evident when the index is computed using the IPC classification (i.e. technologies in this classification scheme are at a more disaggregated level) although it is still possible to observe a decrease in the values between 1994 and 1999 and again between 2002 and 2007. Figure10 displays the trends of the diversification index of the automotive industry over time using the IPC classification.

Table 9: diversification in the automotive industry between 1990 and 2014 computed both using the IPC classification and by using the Schmoch's classification.

Year	Based on IPC	Based on Schmoch
1990	.986315	.9008442
1991	.9866328	.8967526
1992	.9865905	.8984291
1993	.9867789	.8964016
1994	.9863022	.8784707
1995	.985013	.8416035
1996	.9841137	.8471827
1997	.9837527	.8720546
1998	.9835824	.8937257
1999	.9827906	.8831205
2000	.9845146	.8884453
2001	.9853036	.8923607
2002	.9841207	.8960276
2003	.9840086	.8938016
2004	.983332	.8911385
2005	.9834914	.8902217
2006	.9828367	.8890985
2007	.9817005	.8900596
2008	.9835458	.8920135
2009	.9832695	.8987692
2010	.982634	.8925828
2011	.9819471	.8881541
2012	.9818156	.8812208
2013	.9801888	.8623439
2014	.9797273	.8486565

Note that the diversification index is sorted in the table on the base of the IPC values.

Figure10: distribution over time of the industry diversification computed using the IPC classification.



4 Conclusions, implications and limitations

This study provides a first overview of the evolution of the knowledge base of the automotive industry by analyzing the patent portfolio of the top 24 OEMs operating in this sector.

The industry level analysis showed that the technologies characterized by the highest patenting intensity are still related to the mechanical and engineering components of the vehicle, such as for example combustion engines and vehicle's parts. However, it seems that other technologies, mostly related to the electrical components of the product, are gaining notable importance. These findings suggest that both *persistence* in established technological fields and *experimentation* in new technical fields seem to be relevant for incumbents' survival and performance (Bergek et al., 2013). New and originally unrelated fields have increasingly become relevant in the industry with the consequence that OEMs have had to expand the range of technological domains they master to stay abreast of technological advances including a rise in the complexity of the final product (Maxton and Wormald, 2004). This trend may have pushed OEMs toward 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 (Zirpoli and Camuffo, 2009).

This study has a number of limitations. A first set of limitations relates to the use of patent data as a measure of innovation and technological knowledge of firms. In our sample, we are able to trace innovation only under the condition that a patent family has been granted. This limits 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. For these reasons, patents are considered an imperfect proxy of innovation and technological knowledge (Epicoco, 2016). However, the rich source of information embedded in patents make them a valid proxy to capture innovation. In addition, the automotive industry has overall 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. 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, at this stage, 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). 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 for the exploration of this interesting dimension. Another limitation lies in the focus on the evolution of the knowledge base of the automotive industry using an aggregated level of analysis. In future work we aim to complement our findings using a firm level analysis that will enable to explore individual OEM's heterogeneity and technological trajectories, in order to highlight significant deviance from the industry values. This study also overlooks the innovation dynamics of suppliers, which represent a critical source of technological knowledge for this industry. In a future stage of this project, we aim at expanding our dataset to cover the patenting activity of the most important suppliers in this industry. This will allow us to gain a more comprehensive understanding of how the knowledge base of this industry has evolved through the last decades of technological turbulence.

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Appendix A

The appendix A reports the full list of IPC classes that have gained importance over time in the automotive industry.

Table A.1: full list of emerging technological classes of the automotive industry between 1990 and 2014.

Class	Description	Tot. Fam.	% of Tot. distinctive Fam.
H01M	Processes or means, e.g. batteries, for the direct conversion of chemical energy into electrical energy	21,395	5.13
B60L	Propulsion of electrically-propelled vehicles	16,023	3.84
B60Q	Arrangement of signaling or lighting devices	7,727	1.85
G01M	Testing static or dynamic balance of machines or structures	7,217	1.73
H02J	Circuit arrangements or systems for supplying or distributing electric power; systems for storing electric energy	6,185	1.48
H02K	Dynamo-electric machines	5,221	1.25
E05B	Locks; accessories therefor; handcuffs	4,579	1.10
G01B	Measuring length	3,968	0.95
F16B	Devices for fastening or securing constructional elements or machine parts together	3,901	0.94
F02N	Starting of combustion engines	3,569	0.86
G05D	Systems for controlling or regulating non-electric variables	3,546	0.85
H04B	Transmission	2,916	0.70
H02M	Apparatus for conversion between ac and ac, between ac and dc	2,867	0.69
E05F	Devices for moving wings into open or closed position	2,481	0.60
C01B	Non-metallic elements; compounds thereof	2,335	0.56
G06Q	Data processing systems or methods	1,964	0.47
G08B	Signaling or calling systems	1,592	0.38
H02G	Installation of electric cables or lines	1,563	0.37
F25B	Refrigeration machines	1,492	0.36
B60C	Vehicle tires	1,488	0.36
E05D	Hinges or other suspension devices for doors, windows, or wings	1,435	0.34
A61P	Specific therapeutic activity of chemical compounds or medicinal preparations	1,419	0.34
B60P	Vehicles adapted for load transportation or to transport	1,414	0.34
G07C	Time or attendance registers; registering or indicating the working of machines	1,360	0.33
G09G	Arrangements or circuits for control of indicating devices using static means to present variable information	1,160	0.28
E06B	Fixed or movable closures for openings in buildings, vehicles	1,130	0.27
H01Q	Antennas, i.e. radio aerials	1,067	0.26
G10L	Speech analysis or synthesis	895	0.21
E04H	Buildings or like structures for particular purposes	689	0.17
C01G	Compounds containing metals	681	0.16
G01K	Measuring temperature	663	0.16
F02G	Hot-gas or combustion-product positive-displacement engine plants	630	0.15
B66C	Labelling or tagging machines, apparatus	480	0.12
F01B	Machines or engines	418	0.10
C12Q	Measuring or testing processes involving enzymes, nucleic acids or microorganisms	406	0.10

B23D	Planning; slotting; shearing; broaching; sawing; filing; scraping; like operations for working metal by removing material	400	0.10
B62B	Hand-propelled vehicles	380	0.09
B25H	Workshop equipment, e.g. for marking-out work	344	0.08
H04H	Broadcast communication	254	0.06
G07F	Coin-freed or like apparatus	253	0.06
B06B	Vehicle wheels	189	0.05
C10L	Fuels not otherwise provided for; natural gas; synthetic natural gas	157	0.04
C10G	Cracking hydrocarbon oils	120	0.03
E01C	Construction of, or surfaces for, roads, sports grounds, or the like; machines or auxiliary tools for construction or repair	102	0.02
E01F	Additional work, such as equipping roads or the construction of platforms	101	0.02
B01B	Boiling; boiling apparatus	92	0.02
A01M	Devices for introducing media into, or onto, the body	72	0.02
B65F	Gathering or removal of domestic or like refuse	61	0.01
H05G	X-ray technique	56	0.01
B21F	Working or processing of metal wire	56	0.01
G07G	Registering the receipt of cash	52	0.01
F23L	Supplying air or non-combustible liquids or gases to combustion apparatus in general	48	0.01
C25C	Processes for the electrolytic or electrophoretic production of coatings	47	0.01
F23K	Feeding fuel to combustion apparatus	45	0.01
B60F	Vehicles for use both on rail and on road	39	0.01
Total patent families flagged as *emerging*		**118,744**	
Total distinctive patent families in the industry		**416,872**	