The diversity of agents and patent thicket evolution in electric vehicles

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Abstract: The evolution of the inventive process in electric vehicles has been increasingly complex and thus the probability of patent thicket too. However, patent agents (individual inventors, companies, non-practicing entities and alliances) are not homogeneous in interests and abilities. Based on information from the Patent and Trademark Office (USPTO) in the period 1976–2012, it is described: 1) the growing complexity in the inventive activity of electric vehicles; 2) the characteristics and evolution in the inventive activity of agents; 3) the relation with patent thickets. It is shown that the evolution of patent thickets (from low to high complexity) is associated to the evolution of technological knowledge as well as the evolution of the agents.

Keywords: patent thicket; diversity of agents; complexity; electric vehicles; intellectual property; anticommons; patent networks.

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1 Introduction

In the automotive industry, innovation is a complex multi-level process. This characteristic is observed in electric vehicles, which are made up of different subsystems.[1] Each subsystem performs multiple functions co-ordinately. From this perspective, several subsystems located at different levels are required for innovation. At the lowest level of invention (Arthur, 2011), the knowledge of laws or principles of physics allow agents to solve problems associated to design and development of new electric vehicles, motors[2], advanced batteries[3] or innovative systems[4]. At another level, agents doing licensing: independent inventors[5], companies, research centres, universities, governments and partnerships of these same agents.[6] Each agent has specific interests. At another level, we find institutional rules, such as intellectual property rights, in particular patents, which affect the inventive step.

These three levels: the nature of good, agent attributes, and the nature of rules are exogenous variables of the action situation in *analysis and institutional development*, framework suggested by Ostrom (1990, 2005), Hess and Ostrom (2003) and Poteete et al. (2011). This analytical program is useful for the study of the inventive step evolution, in particular the issues of patent thickets.

Electric vehicles use a broad and complex constellation of technologies that no isolated agent is able to develop. For this reason, the inventive step, as it combines previous knowledge (and patents) from other organisations, is able to create "a dense network of overlapped intellectual property rights that a company must hack its way through in order to actually commercialize new technology" [Shapiro, (2001), p.120]. Overlapped property rights are frequently associated to:

1 complex goods

2 high technology fragmentation

3 impossibility to define precisely the knowledge related to patents (Bessen and Muarer, 2008)

4 which escalates given the ambiguous nature of the language (Ostrom, 1980).

Patent thickets could result in expensive and lengthy negotiation processes and thus in substantial transaction costs. At the worst, they could lead to rival agents to mutual obstruction, preventing them from the use of resources such as knowledge embodied in patents. This problem of underutilisation of resources is called 'tragedy of the anticommons' (Heller, 1998, 2008).

Patent thickets and the anticommons tragedy have been studied in biomedical industry (Heller and Eisenberg, 1998), genomics (Van Overwalle, 2009; Osorio and Lara, 2013) and automotive sector (Chávez and Lara, 2016). For Chávez and Lara (2016), the growing complexity of electric vehicles (nature of the good) contributes to explain the patent thicket problem. In order to advance into patent thickets nature, our article examines the role of diversity of agents. From this perspective, the main issues guiding this paper are: during inventive step, how does agent diversity evolve? Does this diversity correspond to electric vehicles complex evolution? Is there a relation between the diversity of agents and patent thickets?

Section 2 presents the taxonomy of diversity is (Page, 2011), which is useful for the representation of technological innovation. In Section 3, based on the United States Patent and Trademark Office (USPTO, http://www.uspto.gov/web/patents/classification/international/est_concordance.htm) information, through the technological network classes, the evolution of the inventive step in electric vehicles for the period of 1976–2012 is analysed. In Section 4, with quantitative indicators, it is examined the agent diversity evolution and technological exploration spaces. Finally, with techniques of analysis and patent thicket indicators (IPO, 2011; Von Graevenitz et al., 2011; Hall et al., 2013), the relation of technological exploration spaces with patent thickets is studied.[7]

2 Technological complexity and diversity

Holland (2004) founds diversity in seven basic elements (mechanisms and properties) present in any complex adaptive system (CAS).[8] Holland (2004), Page (2011) and Low et al. (2003) consider that complexity and diversity are recursive (diversity generates complexity and vice versa) and tend to create robust systems.

Diversity may arise *inside* a type (variation)[9] or *among* types.[10] These ideas could be represented as binary chains. A technology comprised, for example, by five elements arranged in a chain, and each element has two possible states: 0 and 1. Technology A is comprised by the chain *[0, 0, 0, 0, 0]* and technology B by the chain *[0, 0, 1, 1, 1]*. When technology is spread in a specific niche, it may bring a new variation: a new type of technology is born. For example, chain A in a particular environment morphs its second element, thus a new A_m technology exists with the chain [0, 1, 0, 0, 0]. If the environment stimulates the reproduction of A_m and not the one of A, A_m mutant technology will then grow and prevail, whereas the A technology will disappear.[11] Otherwise, if A_m technology is able to recombine with technology A, diversity is then broadened. If recombination of A and A_m is not possible, then A_m represents a new technology (new specie).[12]

Kauffman (1993) constructs a model of fitness landscapes in which a level of fitness is associated to each variation, understood this as its reproduction rate. In such a way that, in all the space of possibilities there will be a reproductive value for each combination and this will form a sort of rugged landscape where each peak and valley represents the fitness value. Frenken et al. (1999) and Frenken (2006) use this model for studying technological evolution.

New technologies are variations of prior technologies. Diverse technologies carry out different functions, for example, technology A [0, 0, 0, 0, 0] performs a F_A function and its variation, technology A_1 [0, 1, 1, 0, 0] complies with the F_{A1} function, but also with the F_A function. In this way, the elements of a given technology may be related in multiple ways to different functions. Combination possibilities are practically endless and the search for an *optimal* technology is, therefore, impossible. For this reason, in different niches several technologies coexist. To this complexity, a technological system carrying out multiple tasks should be added. Some of these tasks may be executed by rival or substitute technologies; whereas others require complementary technologies. In this net of rival and complementary technological relations, lies an important portion of the nature of the inventive step.

Arthur (2011) explains that technology is delimited by the laws of physics. In search of new solutions, a technology may be improved until it reaches a physical limit that leads to other technologies. For example, General Motors Company, in the EV1 (its first electric vehicle) improved the lead acid battery. However, the improvements introduced are not enough; they do not meet the energy storage requirements that efficient electric vehicles demand. The performance of this battery is weak.

As a result of this experience, electric vehicle designers are searching for new solutions: exploring other active materials (lithium-ion batteries, NiMH, etc.) or other knowledge domains (e.g., the fuel cell technology). Thus, when improvement is not enough, a deeper exploration is needed. This means that:

a a given solution may create new problems (Ostrom, 1990; Simon, 1996) which may lead to the structural deepen of the technology, that is, the emergence of subsystems within subsystems (Arthur, 2011)[13]

b new systems need to interact with old ones, so precise interfaces are required.[14]

Considering the USPTO database, it is worth asking how is it possible to examine the relation between:

1 the technological complexity of electric vehicles

2 the diversity of inventor agents.

The first is discussed in the following section and the second in subsequent.

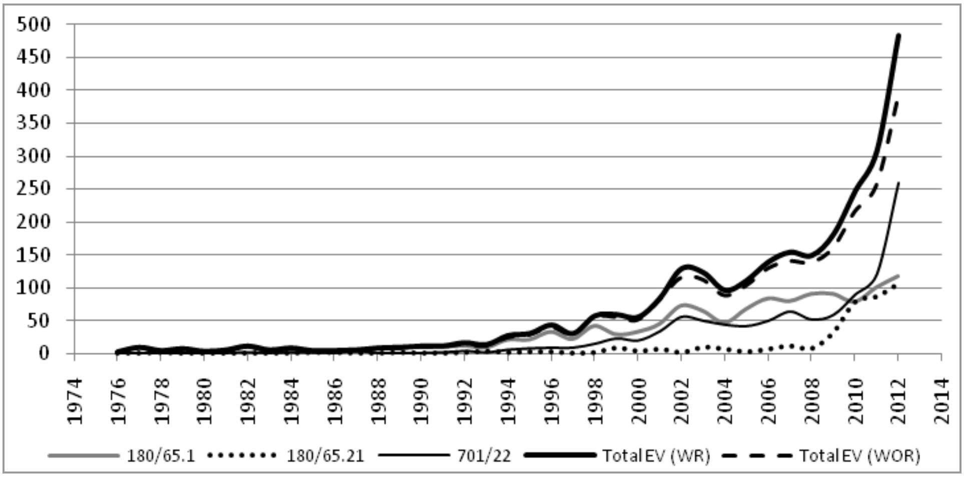
3 The complexity in the invention of electric vehicles

A way to approach electric vehicles technological complexity is through patents. They provide plenty of information on each research areas. Said research areas could be represented through technological classes.[15] Significant knowledge developed by agents is expressed in patents.[16] It could also indicate knowledge transfer between agents.

Our study uses the information of patents related to the USPTO electric vehicles because it is a reliable and accessible database; and because the automotive industry companies seek to protect their inventive activity in the US market, which is one of the most important in the world.[17] From this database, patents belonging to the following classes were selected: 180/65.1 (motor vehicles, electric power), 180/65.21 (motor vehicles, electric power, hybrid vehicle) and 701/22 (data processing, vehicles, navigation, and relative location, electric vehicle). The USPTO patent office considers the invention of electric vehicles in those classes.[18] All patents with at least one of these three classes were selected.[19] The resulting database has 2,358 granted patents, ranging from January 1st, 1976, to November 17th, 2012.

With this information, it is possible to observe (cf. Figure 1) two relevant characteristics of the inventive step related to electric vehicles. In the first place, since 1992, the number of granted patents has been grown exponentially. This phenomenon is closely linked to changes regarding environmental legislation and oil prices variation (Lara, 2014). Secondly, since 2009, the accelerated growth of class 701/22 that matches in 2010 and then surpasses in 2012, the number of patents in comparison to class 180/65.1. This migration of inventive step from the electric motor (tangible component) to data processing (intangible component), evidences quantitative and qualitative transformation of invention processes and therefore, the electric vehicle nature.

Figure 1 Electric vehicles patents (1976–2012)



Notes: All patents include any of the selected classes and some patents may include more than one. The total with repetitions (WR) includes repetitions and total without repetitions (WOR) excludes them.

Source: Own, information obtained from the USPTO, UAM/PECCI database. Project 'Complex Adaptive Systems and Technological Cooperation' CONACyT No. I0017-156204

As indicated in the previous section, a certain technology is comprised by elements interrelated in a particular manner.[20] Thus, each patent is associated to a chain where its elements are the classes. Therefore, a long chain indicates specialised knowledge and a short chain indicates relatively generic knowledge.[21] When two patents share a technological class, a link is created; it is then possible to create a network of classes.[22] Figure 2 illustrates the electric vehicles network classes for the period of 1976–2012. The darker coloured area indicates a higher density network, this means that classes have a higher degree of connectivity. Lighter colours indicate lower connection. Higher connected classes are associated to hybrid vehicles, and to a lesser extent, electric vehicles classes. The less connected, probably due to their newer status, are the data processing classes. The statistics of this network can be found in Table 1.

In the first column of Table 1, the number of nodes is shown. In our case, the number of technological classes used each year. From eight classes in 1976, it grows in an exponential manner to 2,394 classes in 2012. This means agents have explored the design space with greater number of construction blocks (classes). The number of links in the entire period also grew from 16 to 19,669. However, if the density of the network is observed (ratio between total of existing links and total of possible links), it is lower and lower: from 0.571 (1976) it decreased to 0.008 (2012). This means possible combinations of classes are huge, however, only a small portion of the network has been explored and it is concentrated in a couple of specific areas, typical of a complex system. The modularity column confirms this fact. This set of statistics of the class network explains how electric vehicles inventive step is becoming more complex. It is worth asking, whether this complexity and the composition of patenting agents are related.

Table 1 Statistical of EV networks (1976–2012)

	Statistical networks										
Year	*Nodes*	*Unique edges*	*Edges with duplicates*	*Total links*	*Nodes/links*	*Self-loops*	*Diameter*	*Average geodesic distance*	*Groups*	*Density*	*Modularity*
1976	8	16	0	16	0.5	0	2	1.25	2	0.571428571	0.25
1977	30	85	9	94	0.352941176	0	2	1.735556	4	0.204597701	0.453259
1978	49	170	48	218	0.288235294	0	3	1.96918	4	0.159863946	0.430267
1979	63	208	41	249	0.302884615	2	3	2.025699	6	0.115719406	0.48352
1980	73	251	52	303	0.290836653	2	3	2.034903	7	0.104261796	0.494834
1981	94	333	58	391	0.282282282	2	3	2.044817	7	0.081903455	0.542813
1982	143	527	80	607	0.271347249	2	3	2.092327	11	0.055254605	0.588207
1983	160	577	84	661	0.27729636	2	3	2.085469	11	0.048113208	0.582982
1984	188	708	99	807	0.265536723	2	3	2.096084	12	0.042610081	0.579435
1985	198	729	103	832	0.271604938	2	4	2.170442	12	0.039583654	0.587072
1986	209	777	117	894	0.268983269	2	4	2.217165	13	0.038001472	0.605873
1987	223	858	131	989	0.25990676	2	4	2.287036	11	0.036884418	0.594135
1988	253	996	153	1,149	0.254016064	2	4	2.261994	12	0.033189033	0.586849
1989	271	1,056	185	1,241	0.256628788	2	4	2.27151	10	0.030859642	0.583661
1990	280	1,086	281	1,367	0.257826888	2	4	2.257423	12	0.030363543	0.547263
1991	297	1,132	328	1,460	0.262367491	2	4	2.216327	12	0.028301028	0.537372
1992	336	1,327	400	1,727	0.253202713	2	4	2.208493	14	0.025852878	0.514947
1993	356	1,431	498	1,929	0.248777079	2	3	2.209964	14	0.02522551	0.487046
1994	402	1,656	635	2,291	0.242753623	2	3	2.197842	17	0.023051823	0.479149

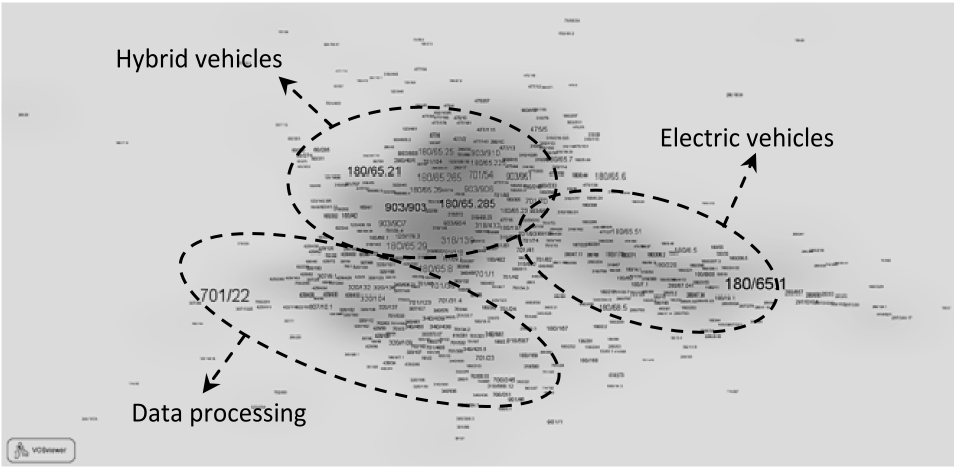
Source: ibid

Table 1 Statistical of EV networks (1976–2012) (continued)

						Statistical networks					
Year	*Nodes*	*Unique edges*	*Edges with duplicates*	*Total links*	*Nodes/links*	*Self-loops*	*Diameter*	*Average geodesic distance*	*Groups*	*Density*	*Modularity*
1995	441	1,776	804	2,580	0.248310811	2	3	2.208997	18	0.020902907	0.463507
1996	535	2,232	1,023	3,255	0.239695341	2	3	2.193261	19	0.017858518	0.455203
1997	585	2,479	1,105	3,584	0.235982251	3	3	2.221866	20	0.016496897	0.470099
1998	662	2,908	1,442	4,350	0.227647868	3	3	2.21514	30	0.015302275	0.444439
1999	744	3,617	2,758	6,375	0.205695328	3	3	2.263647	24	0.015680401	0.416215
2000	811	4,068	3,296	7,364	0.199360865	3	3	2.270525	24	0.014948775	0.399082
2001	910	4,943	4,426	9,369	0.184098725	4	3	2.272018	29	0.014584316	0.348095
2002	1,082	6,709	6,456	13,165	0.161275898	5	3	2.264341	37	0.013995735	0.344776
2003	1,230	7,789	8,121	15,910	0.157915008	6	3	2.291008	39	0.012570204	0.339868
2004	1,294	8,325	9,338	17,663	0.155435435	7	3	2.286256	50	0.012208169	0.318373
2005	1,392	9,021	10,409	19,430	0.154306618	9	3	2.279286	73	0.011487022	0.327287
2006	1,473	9,623	11,210	20,833	0.153070768	10	3	2.272887	50	0.010941512	0.326016
2007	1,587	10,396	11,979	22,375	0.152654867	11	3	2.287462	37	0.010147073	0.335135
2008	1,662	11,069	12,982	24,051	0.150149065	15	3	2.278327	47	0.009893566	0.318214
2009	1,800	12,348	14,658	27,006	0.145772595	17	3	2.270465	51	0.00948984	0.329608
2010	1,922	13,682	16,634	30,316	0.140476539	24	3	2.280906	53	0.009272074	0.316975
2011	2,124	15,957	19,115	35,072	0.133107727	33	3	2.281611	51	0.008828072	0.311535
2012	2,394	19,669	23,895	43,564	0.121714373	57	3	2.277313	36	0.008603135	0.303294

Source: ibid

Figure 2 Electric vehicles class network (1976–2012)



Source: ibid

4 Diversity of agents

4.1 Type of agents and general characteristics

Knowledge contained in patents is finally, result of human effort. It is, therefore, of great importance to understand two characteristics regarding the *organisation* of this effort:

a whether it is an individual or collective result

b whether it is able to deal with intellectual property rights and with abilities to transform inventions into innovations.

The patent office[23] assigns intellectual property rights to a broad diversity of agents: inventors, companies, non-practicing entities[24] (NPEs) and partnerships, among others. These categories are useful to characterise some attributes in agents, particularly economic and non-economic intentions when patenting. In the case of electric vehicles, private firms or companies are the main type of patenting organisation; 79% of patents belong to 350 companies, 13% to 271 inventors, 4% to 25 partnerships, and 3% to 35 NPEs (cf. Table 2).

In addition to the wide range of intentions of agents, there are quantitative and qualitative differences regarding to the type of knowledge each agent is contributing to (cf. Table 2). *NPEs* have the higher number of average claims[25] (17.2) the same happens with its forward citations[26] and the average of classes[27] and their backward citations, furthermore, the average number of inventors[28] surpasses general average. This indicates that, even if the NPEs weight is small, they contribute with new and complex patents in 3% as a proportion of the total.

Meanwhile, *companies* present more diverse knowledge with average claims (15.2), backward and forward citations comparatively lower and a relatively high number of classes and inventors: 5.5 and 2.6, respectively (cf. Table 2). In the case of *partnerships*, it is a fundamentally specialised knowledge; they have a very low average of claims (13.7) and forward citations[29] (3.5). From the number of classes (5.2) under the average, it can be said that inventive step of partnerships is related to few domains, but rather with knowledge previously generated (high backward citations, 74.6) and with the highest number of inventors (3.3). Finally, in the case of *inventors*, previous knowledge cited is low (15.4) as well as their claims (13.5), the domains in which they operate are relatively few (4.5 classes) and with small number of inventors (1.3 inventors per patent). It can be said that inventor's generated knowledge is relatively simple. In summary, the NPEs knowledge is new and complex, the one of companies is diverse, the one of partnerships is specialised and the one coming from independent inventors is relatively simple (cf. Table 2).

Table 2 Participation and qualitative diversity in the knowledge of agents

Agent	*Agents participation*			*Average indicators*				
	Number of agents	*Patents*	*% of patents*	*Claims*	*Forward citations*	*Backward citations*	*Number of classes*	*Number of inventors*
Companies	350	1,865	79.09	15.22	8.2	18.71	5.55	2.66
Partnerships	25	98	4.16	13.78	3.56	74.68	5.23	3.35
NPE	35	78	3.31	17.23	16.67	25.3	5.61	2.96
Inventors	271	317	13.44	13.57	12.26	15.45	4.57	1.3
Average				15	8.83	20.82	5.41	2.52

Source: ibid

What is the importance of each agent in patents development? Different types of agents contribute in differential manner to the inventive step. Only five agents (all of them companies: Toyota, Honda, General Motors, Ford and Nissan) have more than 100 patents, the rest produce less than 50. Of the 20 agents with more patents, two are partnerships[30] (which evidences the importance of this type of organisation), and two are companies not belonging to the automotive industry.[31]

In the case of companies, Table 3 represents the ten main companies for the period from 1976 to 2012. Honda's leadership is observed in the period 2000–2007 and Toyota's from 2008 onward. Likewise, in the last four years, General Motors peak is also noted, this is mostly explained by its partnerships with other companies.

When examining the period 1976–2012 in further detail, the following is noted. A small group of companies (16 from 1976 to 1982 and 19 from 1983 to 1988) patented in these two initial periods. However, since 1990, this population grows until reaching 234 companies, in the last period (2006–2012). How does leadership evolve in the inventive step? In initial periods (1976–1982 and 1983–1988), the leading companies were Lucas Industries and Peg Perego Pines[32], in the first and second period, respectively. In both periods, the automotive industry inventive step was very low. In the subsequent periods emerge Japanese company's leadership, Aisin (Toyota's subsidiary), Honda and Toyota and to a lesser extent the USA (GM, Ford) and European (BMW) firms.

Table 3 The ten main companies patenting in EV (1976–2012)

Company	*1977*	*1978*	*1980*	*1987*	*1989*	*1990*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*Total*
Toyota	1									1	1	3	3	10	3	2	6	8	6	6	6	12	13	24	38	47	92	282
Honda									4	5	6	3	3	9	6	10	14	16	13	20	14	16	12	17	9	16	8	201
GM			1					1			2	2	0	0	0	0	3	3	4	8	6	12	4	10	15	34	67	172
Ford		1							1	2			1	1	1	6	7	9	11	6	9	12	5	5	21	11	17	126
Nissan					1	1		1		1	1				1	7	8	6	6	5	11	8	5	6	11	8	13	100
Aisin							1	2	2	1				2	1	1	1	6	3	3	8	6	6	3	2	8	10	66
Hitachi				1						1	4	1	1	1		1	3	5	3	3	3	4	6	3	2	3	6	51
Denso	1														1	2	1			1	2	1	1	2	7	9	21	49
BMW																							3	3	1	6	28	41
Mitsubishi				1							1		2	1	1	1	3	1		2	2	1	1	6	2	5	5	35
Total	2	1	1	2	1	1	1	4	7	11	15	9	10	24	14	30	46	54	46	54	61	72	56	79	108	147	267	

Note: Includes patents granted in partnership.

Source: ibid

Partnerships have turned into a key element of the inventive step for two reasons:

a because by cooperating with other company, it is possible to produce specialised knowledge

b in the event of possible blockages, partnerships increase their bargaining power.

During the entire study period, 25 alliances were formed. The 33 patents of Global Hybrid Cooperation partnership (BMW, Chrysler, Daimler and General Motors) stand out. Followed by Toyota with six partnerships and General Motors with four of them.

From the point of view of partnership evolution, three moments are distinguished. With exception of the first partnership – Toyota and Denso in 1977 – during the first 19 years of the period, no partnership was registered. During the following decade – since the Toyota-Kanto partnership in 1996 – one to two partnerships per year were created. And since 2007, patents resulting from partnerships have grown exponentially. Particularly, during 2011 and 2012, 11 partnerships registered 66 patents, which represent 67.34% of patents generated by partnerships.[33] Everything indicates that in the future, partnerships will become a mechanism to produce specialised knowledge.

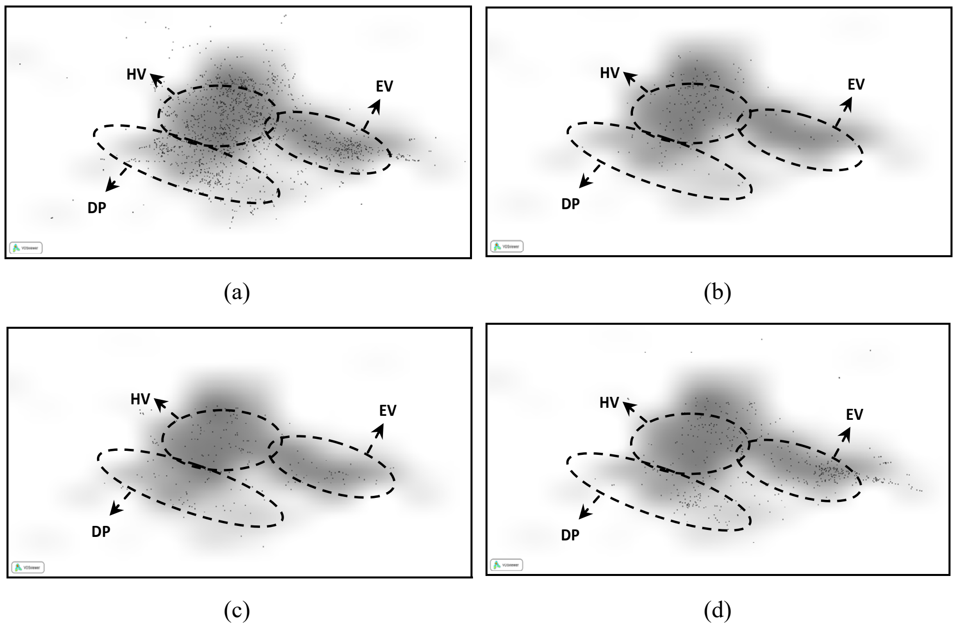
On the other hand, there are 35 NPEs. It is observed, that private research centres provide the greatest number of patents: DEKA (an independent centre) and Equos Research (Toyota's investigation centre) with 14 and 12 patents, respectively. Followed by *Industrial Technology Research Institute*, a Taiwanese public institution and a private research centre called *Paice*[34], (both with four patents). The rest of NPEs have three or less patents. As mentioned above, NPEs are an important source of deep knowledge (cf. Table 2), however, depending on the strategies they chose (grant licenses or not), they may become an advantage or an obstacle for electric vehicles innovation.

Which technological classes do these agents concentrate in? Figure 3[35] is showing agents distribution in the network of technological classes. The knowledge of companies [cf. Figure 3(a)] represents 86.21% of total classes. If all its subsidiaries and partnerships classes are added to Toyota, it represents 25.31%. This level reflects the limitations; even the agent with the greatest amount of resources in the automotive sector is unable to cover all technological classes.

In the case of partnerships [cf. Figure 3(b)], their inventive step is concentrated in the densest spaces of the network, where there is more developed knowledge and particularly in the area corresponding to hybrid vehicles. This type of agent is linked with 231 classes (9.64% of the total system). Its importance does not seem to lie in the volume of classes, but in the knowledge integration that it carries out.[36] For its part, NPEs knowledge [cf. Figure 3(c)] is not extended throughout the entire network nor is it in more densely populated areas. NPEs provide the system with knowledge in scarcely explored areas, which is consistent with its own research activity. This fact is reflected in its high number of forward citations (cf. Table 2). It is a pioneer agent. Lastly, inventors' knowledge, as well as companies one, also extends throughout the network, mainly in the densest areas [cf. Figure 3(d)], but with certain bias (17.09% of its classes) towards small electric vehicles such as wheelchairs or golf carts.

In short, these four agents maintain qualitative and quantitative differences. Average data is important because it provides a general image of each agent's contribution. However, in order to properly characterise the knowledge delivered by each agent, a more in-depth analysis is required. This is examined further in the next section.

Figure 3 The distribution of agents in EV class network (1976–2012), (a) companies (b) partnerships (c) NPE (d) investors



Note: HV: hybrid vehicles, EV: electric vehicles and DP: data processing.

Source: ibid

4.2 The evolution of agents and their knowledge in the electric vehicles invention

How has the knowledge of agents evolved in the inventive activity of electric vehicles? Information regarding the entry of new agents and classes will allow us to move towards the answer. Figure 4 shows that during the period from 1976 to 1991 the number of new agents grew.[37] The number of new agents – companies and inventors – increases lightly (from two to ten agents, approximately one new agent every two years). From 1992 onward, the number of new agents grows, mainly companies.[38] Particularly, in 2011 and 2012, companies entered and new partnerships were formed.[39] The increasing number of new participants is associated to the expansion of the exploration space.

Since the beginning of the reference period and for 15 years, a few new classes were incorporated to the electric vehicles sector (cf. Figure 5). However, in the '90s, new classes grew exponentially. There are three maximum peaks:

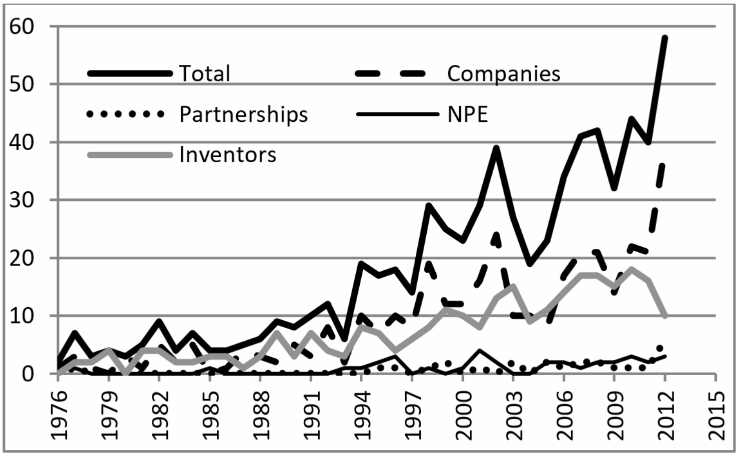
1 in 2002, 172 new classes were integrated

2 in 2011, 202 new classes

3 in 2012, 270 new classes.

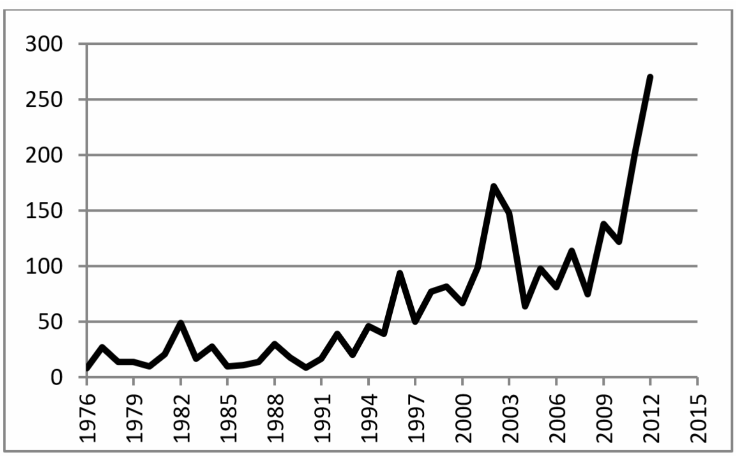
The expansion of new technological classes follows the fact that during the '90s, in order to design and develop electric vehicles technological and economic competition begins. Competition pressures companies to improve and build complex nested systems. As a result, in order to validate those new exploration spaces institutionally, patent offices were required to create new technological classes.

Figure 4 New agents in EV (1976–2012)



Source: ibid

Figure 5 New classes in EV (1976–2012)

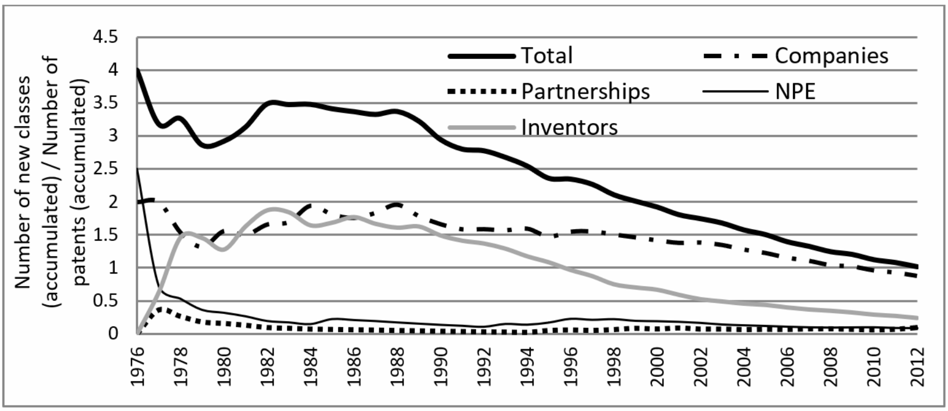


Source: ibid

It is worth asking whether the exploration intensity for new classes is different from one agent to another. In order to get an indicator representing the intensity with which agents explore new classes, an indicator is developed[40] (cf. Figure 6). During the first years (1976–1979), although distributed, innovation searching was more intense in companies and inventors. During the '80s, the innovation searching intensity is relatively constant for partnerships and NPEs (on average, at rates of 0.08 and 0.2, respectively), and more intense in the case of companies and researchers (1.75 and 1.66, respectively, on average). However, during the '90s, search intensity for new classes decreases, especially the one of inventors (from 1.49 in 1990 to 0.23 in 2012) and companies (from

1.66 in 1990 to 0.87 in 2012). During the same period, in the case of partnerships, this rate is practically non-existent, and small in the case of NPEs. In short, during the period, new classes were explored but intensity on exploration decreased. This implies that inventive step tends to recombine technological classes with those they had patented in past periods. Consequently, seeking for a delimited space leads to redundant or overlapped research areas.

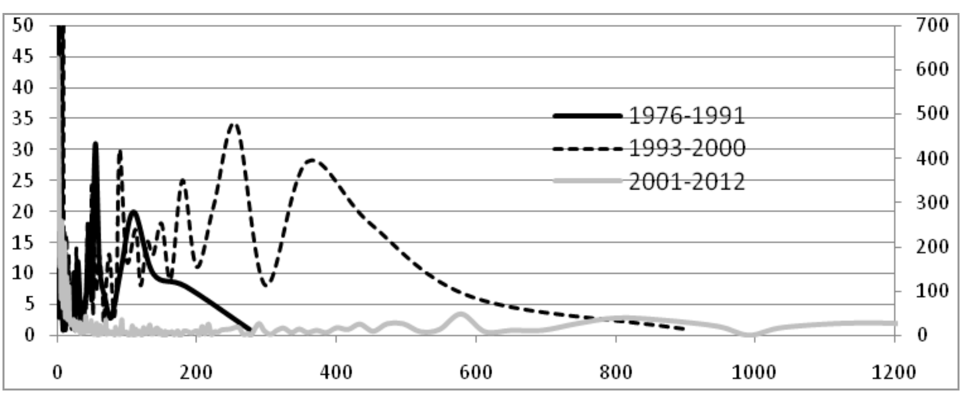
Figure 6 Intensity of exploration of new classes in EV (1976–2012)



Source: ibid

From the point of view of technological classes, how to distinguish whether the agents search, is concentrated or diversified. For that purpose, concentration coefficients are calculated for the periods of 1976–1991, 1992–2000 and 2001–2012[41] (cf. Figure 7). If inventive step were *specialised*, it would show a normal probability distribution with low variance and this would be represented in the limit as a vertical line. If inventive step were *diverse*, then probability distribution would be normal with a large variance and this would be represented in the limit as a horizontal line.

Figure 7 Distribution of EV concentration indexes by periods*



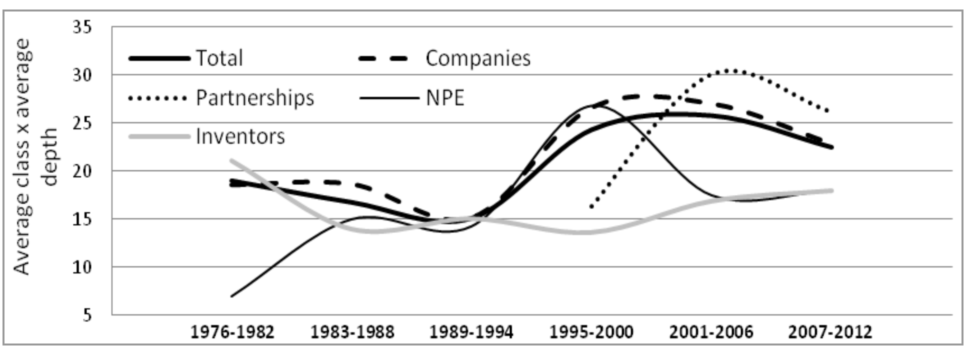
Note: *The first two periods scale is on the left and the last period scale on the right.

Source: ibid

From Figure 7, the following is noticed: in the three selected periods, the results of the electric vehicles invention system, showed a probability distribution of the 'power law' type, accentuated as time goes by (cf. Figure 7). This means that search pattern of agents is concentrated in specific groups of technological classes, where specialisation and diversification coexist.

In this regard, it would be suitable to analyse how agents provide knowledge to the system while participating in the inventive step. Therefore, it is necessary to represent a patent specification and its knowledge depth.[42] Figure 8 reflects the evolution by periods regarding the product, of the average number of classes multiplied by the average of its depth for each type of agent. In the first period (1976–1982), it can be seen that except for NPEs, the type of knowledge of all agents, regarding their level of specification and depth is similar. In the following two periods (1983–1988 and 1989–1994), companies, as well as NPEs provided the system with the most in-depth and specific knowledge. As noted above, the contribution of NPEs does not lie so much on the number, but rather on their patents quality, as it has the highest average level of forward citations and claims (cf. Table 2). In the period 1995–2000, it was companies, and in the period of 2001–2006 it was partnerships, that contributed with the more specialised and in depth knowledge to the system. After reaching a maximum, companies and partnerships contribution decreased in the period 2007–2012, being partnerships the ones with the higher contribution activity. Except for the first, individual inventors contribute with relatively few knowledge in all periods.

Figure 8 Evolution of average of classes and depth in EV by periods (1976–2012)



Source: ibid

In order to enrich this description, Table 4 shows the frequency and depth of classes for each type of agent.[43] Partnerships have specification range from 1 to 31 classes (a high range) even though all of its statistical modes are relatively low.[44] On the other hand, companies have the highest degrees of specification (35 classes) and depth (level 8).[45] Modal specification for this type of agent is relatively high (five classes), but depth is concentrated in two. Thus, companies contribute to the system with the longest and deepest knowledge chains.

Table 4 Class frequency according to specialisation and depth level for each type of agent in EV (1976–2012)

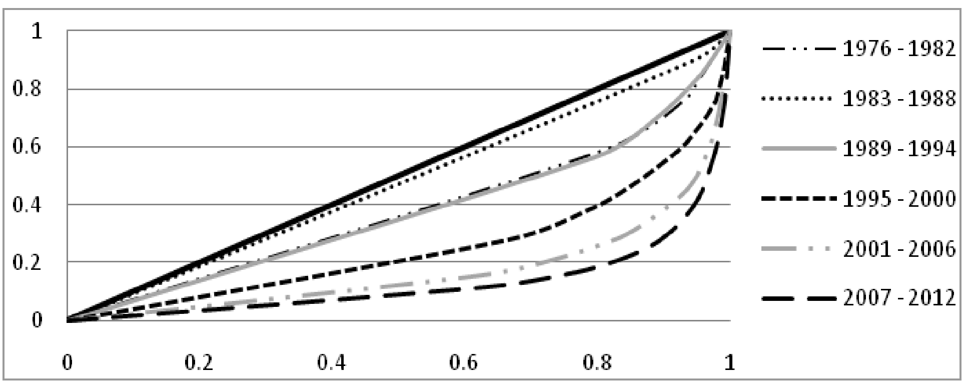
Agent/depth	*Number of classes*																										
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*25*	*26*	*31*	*32*	*35*
Partnerships	*8*	*28*	*72*	*48*	*50*	*30*	*35*	*40*	*9*	*30*	*44*		*13*	*28*	*30*		*17*									*31*		
1			3	3	2		7	4		4	3		2	3	4		3									5		
2	8	14	25	23	18	10	14	15	6	6	10		4	9	7		6									12		
3		10	23	11	13	9	7	8	1	13	13		5	7	8		3									6		
4		4	14	6	11	6	2	3	2	4	13		2	7	4		2									7		
5			7	4	5	3	5	7		2	5			2	6		1									1		
6				1	1	2		2							1													
7								1		1							2											
Companies	*46*	*466*	*1,023*	*1,220*	*1,240*	*1,074*	*805*	*680*	*657*	*530*	*583*	*432*	*286*	*280*	*195*	*96*	*136*	*72*	*133*	*100*	*84*	*66*	*46*	*25*	*26*		*32*	*35*
1		21	103	149	137	119	90	70	67	56	57	43	32	17	24	9	13	6	11	11	12	7	4	1	1		1	4
2	46	292	464	521	478	365	283	216	202	149	179	129	83	73	67	34	27	18	45	30	28	17	14	6	6		8	3
3		95	240	258	287	285	201	183	157	127	174	118	70	74	48	24	39	20	36	22	20	17	17	5	9		8	10
4		29	129	160	167	147	99	91	114	83	80	74	43	46	25	14	25	9	17	15	16	12	4	7	8		6	9
5		20	71	102	127	132	103	94	85	84	70	48	40	49	24	9	25	12	18	20	8	12	5	4	2		6	6
6		9	15	25	40	23	29	26	30	31	21	20	18	17	7	6	5	7	5	2		1	2	2			3	1
7				5	2	3			1		1			4			2		1									1
8			1		2				1		1																	1
NPE		*10*	*42*	*56*	*50*	*66*	*42*	*40*	*54*	*30*	*33*				*15*													
1			9	4	15	4	11	8	12	4	4																	
2		5	16	24	10	20	15	11	15	7	8				2													
3		3	9	17	12	19	8	9	17	11	9				5													
4			5	6	8	9	5	4	5	4	3				2													
5		2	3	5	4	11	2	6	4	2	8				5													
6					1	3	1	1	1	2	1				1													
7								1																				
Inventors	*3*	*80*	*249*	*292*	*205*	*138*	*154*	*104*	*45*	*30*	*33*	*12*	*26*		*15*	*48*	*17*											
1		10	40	49	34	19	32	14	5	6	3	3	2		2	11	1											
2	3	42	128	113	83	50	51	33	11	8	7	7	2		2	15	3											
3		22	41	59	45	25	23	23	10	9	7	1	9		3	9	3											
4		5	32	42	31	24	34	20	14	5	11	1	4		3	10	3											
5		1	6	20	11	18	12	9	3	1	4		8		4	3	4											
6			2	8	1	2	2	5	2	1	1		1		1		2											
7				1													1											

Source: ibid

In turn, NPEs show a degree of specification varying between 2 and 15 classes. This is an agent with high level of specification (mode of six classes) and a depth level similar to the rest of agents (mode of 2). Finally, inventors contribute with diverse knowledge to the system: they have the lowest specification levels (the mode of their classes is 3) and low depth (mode of 2). In summary, partnerships and NPEs contribute with specific and deep knowledge to the system. Companies contribute with diverse knowledge in both specificity and depth. And finally, inventors contribute with diverse knowledge but with relatively low specificity and depth.

From the agent point of view, it is worth asking, how knowledge diversity contained in patents is distributed? Is it dispersed or concentrated? It is possible to find answers in the way Lorenz curves evolve for the period 1976–2012 (cf. Figure 9).[46] The first period (1976–1982) has a moderately distributed curve; knowledge is just slightly concentrated. Whereas the curve for the period (1983–1988) is straighter, knowledge is more distributed.[47] It is from the third period (1989–1994) onward, when Lorenz curves tend to move away from the main diagonal. That is to say, from the third period onward a small group of agents concentrates a greater number of patents.

Figure 9 Lorenz curves for EV



Note: Sub-periods from 1976 to 2012.

Source: ibid

This means that throughout the inventive step related to electric vehicles, agents enter and new research areas are created (see Figures 4 and 5) but the degree of inventive activity concentration is growing. How are these growing concentration levels explained? One plausible reason for this behaviour lies in the complexity of electric vehicles design and development. Only those agents with accumulated experience, abilities and significant resources have the greatest probability of solving complex problems. This tendency towards concentration is attenuated when problems in electric vehicles design and development pop up, the creation of new technological domains are required. There is no dominant design for electric vehicles. Technology is in a fluid state. This situation creates opportunities for new agents to enter in the sector. This partly explains the coexistence of more concentrated inventive step with new agents entry.

Table 5 Classes with patents registered in by ten main companies in EV (1976–2012)

Class	Year 1978	1980	1987	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total
29																				GM								1
37																	HO		HO	HO								3
48																							N					1
60								A					T		HO	N	HO	N	GM, HO	T		HI		BMW, T	GM, N	GM, M, T		17
62									HO																		T	2
73																				HO						F		2
74					N											D									GM	N	T	5
116																											D	1
123													T	HO	N	D, HO, N	F, GM, HO	HO	A, F, GM, T	F, HO	T	F		M, T	GM, T	GM, M, N	D, F, T	28
137																								HO				1
141																					HO							1
148																											N	1
165												HI								HI	D					T	F, GM, T	7
174																								HO				1
180	F	GM	HI	N	N	T	A	A, GM, N, T	A, F, HO	A, F, HO, N, T	GM, HI, HO, M, N	GM, HI, HO, T	F, HO, M, T	A, F, HO, M, T	D, F, HO, M, N, T	A, D, F, HI, HO, M, N, T	A, D, F, GM, HI, HO, M, N, T	A, F, GM, HI, HO, M, N, T	A, F, GM, HI, HO, N, T	A, F, GM, HI, HO, N, T	A, D, F, GM, HI, HO, M, N, T	A, F, GM, HI, HO, M, N, T	A, BMW, F, GM, HI, HO, M, N, T	A, BMW, D, F, GM, HI, HO, M, N, T	A, BMW, D, F, GM, HI, HO, M, N, T	A(2), BMW, D, F, GM, HO, M, N, T	A, BMW, D, F, GM, M, N, T	146
184																		HO										1
187																							T				M	2
188		GM							HO	HO, T		GM			T	F	GM										N	9
191																										T	T	2
192																N		N		F		HO		A	N		T	7

Notes: Aisin (A), Bayerische Motoren Werke (BMW), Denso (D), Ford (F), General Motors (GM), Hitachi (HI), Honda (HO), Mitsubishi (M), Nissan (N) and Toyota (T). Each abbreviation indicates a technological class in which the respective company patented. If in the same year the company patented more than once in the same technological class, it is indicated in parentheses as many times as it did.

Source: ibid

Table 5 Classes with patents registered in by ten main companies in EV (1976–2012) (continued)

Class	*Year*																											*Total*
	1978	*1980*	*1987*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	
200								N																				1
204																						N						1
220																					HO							1
228																				GM								1
235																				N								1
237										F		HI						F										3
248																					HO							1
257																				HI								1
267																						F						1
280											N			HO	HO		HO			HO	GM, HO	GM		F, HO, T	D, F, HO, T	T	T	17
290								GM							T	D	F, HI, T	HI, N	HO, T	A, HO, N, T	A, HI, M, N	F, GM, HI, N	GM	F, T	D, GM, N, T	D	N, T	32
296											N								GM	GM	GM, HO	GM		HO,, T	HO			9
297															HO										HO		T	3
301																										T		1
303		GM							HO	F, HO, T	GM	GM			HO, M, T	F	GM		F	N	F	HO			F		GM	18
307						T			HO		HO		F	F, HO			T	T	F, HI	F, GM, HO	A, F	HI	D	D, HI	GM, T	D, F, GM, HO, T	BMW, D, F, GM, T	31
310	F										HI	HO		HO, T		D				HI, HO	N	N		F, GM, HO, M	HO, T	GM	GM	18
318		GM	HI, M			T	A	T	A, HO	A, HI, HO, N	GM, HI, HO	T	HI, HO, T	A, F, HO, T	HO, T	F, HO, M	D, F, HI, HO, M, N, T	A, F, GM, HO, N	F, HI, HO, N, T	A, F, GM, HO, M, T	A, D, F, GM, HI, HO, N, T	HO, M, N	HI, HO, T	D, F, GM, HI, HO, M, N, T	BMW, D, HO, N, T	A(2), D, GM, HO, T	A, D, GM, M, N, T	90

Notes: Aisin (A), Bayerische Motoren Werke (BMW), Denso (D), Ford (F), General Motors (GM), Hitachi (HI), Honda (HO), Mitsubishi (M), Nissan (N) and Toyota (T).
Each abbreviation indicates a technological class in which the respective company patented. If in the same year the company patented more than once in the same technological class, it is indicated in parentheses as many times as it did.

Source: ibid

Table 5 Classes with patents registered in by ten main companies in EV (1976–2012) (continued)

Class	*Year*																											*Total*
	1978	*1980*	*1987*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	
320										F		HO	HO	HO		HO	M, T	N, T	A, F, HO	A, GM, HO, T	F, N	T	HI, HO, N, T	BMW, F, HO, N, T	D, F, GM, N, T	F, GM, M, T	A, BMW, D, F, GM, N, T	44
322													HO		T		F, M, T	A, GM		F, M, T		F		D	D		GM, N	15
323																					M			N				2
324										F								F		M						GM	D,, T	6
326																								HI				1
340									HO		HO	HO					F		F	N	HO, N	GM	F, HO	T	F, GM, M, T	BMW, D, F, GM, T	D, F, GM, N, T	26
345																											N	1
348																											T	1
361			HI					T			HO			HI						HI, HO					D, HO	T	A, GM, M, T	13
363																		HI		HI				N		A, GM	A, GM, T	8
367																											D	1
375																							HO					1
379																										GM	GM	2
381																											D, N	2
388																								GM, N				2
414																										F		1
417																											T	1
422																							N					1
429											HI, HO	HI			T		GM, N	HO, M	HO, T	GM, HO	D, HO, N	HO, N, T	HO, N, T	M, N, T	F, M, T	GM, N, T	D, N, T	33
439																			GM									1
440																				HO								1

Notes: Aisin (A), Bayerische Motoren Werke (BMW), Denso (D), Ford (F), General Motors (GM), Hitachi (HI), Honda (HO), Mitsubishi (M), Nissan (N) and Toyota (T).
Each abbreviation indicates a technological class in which the respective company patented. If in the same year the company patented more than once in the same technological class, it is indicated in parentheses as many times as it did.

Source: ibid

Table 5 Classes with patents registered in by ten main companies in EV (1976–2012) (continued)

Class	*Year*																											*Total*
	1978	*1980*	*1987*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	
446																								HO				1
454									HO												GM	HO			HO			4
455																									F	GM	D	3
474																										GM		1
475											GM	T					N	A		HO		A, GM	N	GM, T	A, GM, T	GM, T	GM, T	17
477									HO				T	HO, T	A, HO	F, HI, HO, N	HO, N	A, F, GM, HI, HO, N	A, F, N, T	A, F, HO, N, T	A, F, GM, N	A, F, GM, HO, T	F, GM	A, M, T	F, GM, N, T	GM, M, N, T	A, BMW, F, GM, N, T	55
700																		T		GM		M	HO	HI, HO	F	D	D, F, T	11
701			HI, M			T	A	A	A, F, HO	A, F, HI, HO, N	GM, HI, HO	HO, T	HI, HO, M, T	A, HI, HO, M, T	A, D, F, HO, N, T	D, F, HO, M, N, T	D, F, GM, HI, HO, M, N, T	A, F, GM, HI, HO, N, T	A, F, GM, HI, HO, N, T	A, D, F, GM, HO, M, N, T	A, D, F, GM, HI, HO, M, N, T	A, D, F, GM, HI, HO, N, T	A, BMW, D, F, GM, HI, HO, N, T	A, BMW, D, F, GM, HI, HO, M, N, T	A, D, F, GM, HI, HO, M, N, T	BMW, D, F, GM, HO, M, N, T	A(2), D, F, GMM, N, T	130
702																	T					HO	HO		F, GM		T	6
703																						F						1
704																							HO					1
705																		HO							D		D, T	4
707																				M								1
713																								D			D	2
714																		T									A	2
901																							HO	HO			T	3
903								A	F		GM	T	M, T	A, HO, T	D, HO, N, T	A, D, F, HI, HO, M, N, T	A, D, F, HI, HO, M, N, T	A, F, GM, HI, HO, N, T	A, F, HI, HO, N, T	F, HO, N, T	HO	A, F, GM, HI, HO, N, T	A, F, HI, N, T	BMW, D, GM, HO, M, N, T	D, F, GM, HI, HO, N, T	A, D, F, GM, HO, M, N, T	A, D, F, GM, M, T	87
Total	2	4	6	1	2	4	3	11	16	22	22	17	19	27	31	40	56	53	49	71	57	57	48	80	80	78	104	960

Notes: Aisin (A), Bayerische Motoren Werke (BMW), Denso (D), Ford (F), General Motors (GM), Hitachi (HI), Honda (HO), Mitsubishi (M), Nissan (N) and Toyota (T).
Each abbreviation indicates a technological class in which the respective company patented. If in the same year the company patented more than once in the same technological class, it is indicated in parentheses as many times as it did.

Source: ibid

From this perspective, it is worth examining the evolution of classes with patents registered in by ten main companies in EV development without considering the partnerships of these companies (cf. Table 5). This information allows representing the evolution of companies searching pattern. It can be observed, that since 1976 until late '80s, companies registered patents in a small group of technological classes related to electric motor, battery, energy carrier system, and mechanical elements (mainly class 180).[48] However, from the '90s onward, there is an expansion of the classes that companies are concentrated in. In particular, during the '90s and the first half of 2000, companies concentrated in the development of electric motors, in hybrid vehicles (mainly class 903), energy accumulation systems (mainly classes 318 and 320)[49], data processing systems (mainly class 701) – associated to electronics growth and computing in vehicles[50] – and in regenerative braking system of electric vehicles. Finally, from mid-2000 up to 2012, new technological classes are added to those of the previous period: development of computing electronic interconnection systems and communication systems, as well as energy control and administration systems (mainly class 477 and all the 700's). The emergence of these classes brings a deep qualitative change to the inventive step: search pattern changes from technological classes of tangible nature (motor, battery) to intangible nature classes (software).

Table 5 shows explored areas by one or various agents as well as empty areas. Toyota is a company related to a large number of classes. Insofar, as Denso and Aisin are Toyota's subsidiary companies, it can be noted that Toyota registers patents in classes belonging to the electric vehicles spectrum (25.35% of the classes). Denso's specialisation in a few classes and Aisin's class diversity are combined with Toyota's searching capabilities. Honda is present in a broad and in some cases, specialised diversity of technological classes. It explores similar areas to Toyota, but also areas where Toyota is absent. If General Motors and Ford are compared as a whole with Toyota, these firms are present in a few technological classes (20.71% taking into account their partnerships and subsidiaries). Nissan, though it has fewer patents, is capable also of exploring relatively diverse group of classes, with specialisation in some of them. For their part, Hitachi and Mitsubishi are more specialised in the main domains with some patents in little explored areas. Finally, thanks to its partnerships in recent years, BMW manages to get on the list of the ten companies with the greatest inventive activity regarding to electric vehicles; however, it specialises in traditional domains. Thus, given the limited (material and cognitive) resources, there is no single company capable of exploring the technological classes ensemble associated to electric vehicles. In this sense, technological competition and cooperation relationships are created between companies.

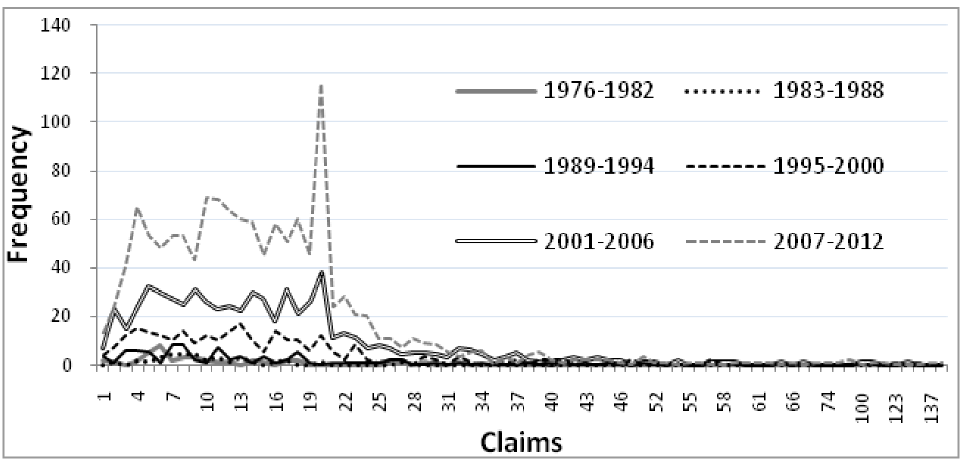
Understanding rivalry or complementarity spaces depends on the way agents build, accumulate and appropriate of technological knowledge through patents. Problems emerge when, in order to commercially exploit a technology, it is necessary to assemble a variety of patents. The following section aims to determine the possible existence of patent thickets.

5 Patent thickets evolution in electric vehicles

Distinct techniques have been developed in order to identify patent thickets (IPO, 2011; Von Graevenitz et al., 2011; Hall et al., 2013) some of them (Lorenz curves and concentration indexes) were examined above. In order to deepen this analysis, three indicators are included: claims frequency, forward citations frequency and backward citations frequency.

The claims determine intellectual property rights. The more claims a patent owner has, the greater his right to exclude others from a technological area.[51] Figure 10 shows the claims frequency distribution for six periods. For the first and second periods, the curves are relatively flat, indicating low probability of patent thickets. However, in the following four periods, the claims frequency grew, and their distribution tends towards a single tail, indicating an increasing probability of patent thickets.

Figure 10 Claims frequency for EV by periods (1976–2012)



Source: ibid

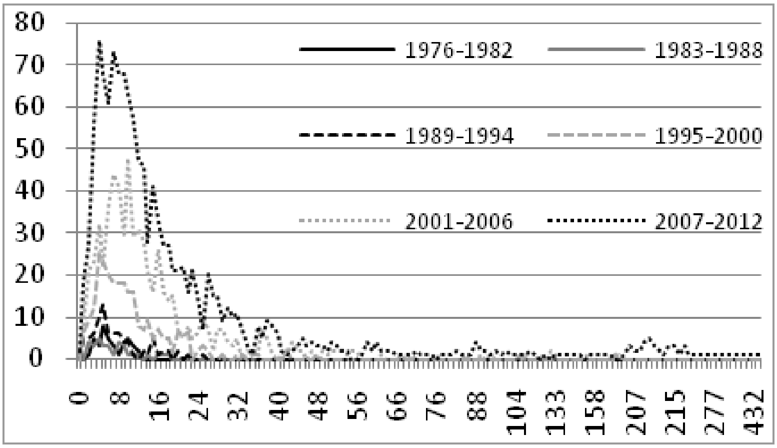
Another indicator of patent thickets is the frequency distribution of *forward* and *backward* citations.[52] If backward citations mode moves vertically away from the origin, the patent is widely cited and therefore, the possibility of patent thickets increases. It occurs similarly for forward citations. The more vertically away from the mode the more cited patents are. Figure 11 shows backward citations frequency distribution for electric vehicles and in Figure 12, forward citations frequency distribution.

Regarding *backward citations* (cf. Figure 11), during the first three periods, a low level can be observed for both volume and frequency of citations. However, in the fourth period (1995–2000), even though the mode is not significantly altered, the right side of the curve moves away from the origin, which means a new patent ensemble, has a greater number of backward citations. From 2001 to 2006, this phenomenon is repeated, however, mode and curve move further to the right. In the period (2006–2012), a contradictory phenomenon appears, on the one hand, the mode moves to the left, whereas the curve's left side takes a bimodal form. This can be explained as a result of two factors:

1 creation of new or diverse, technological classes

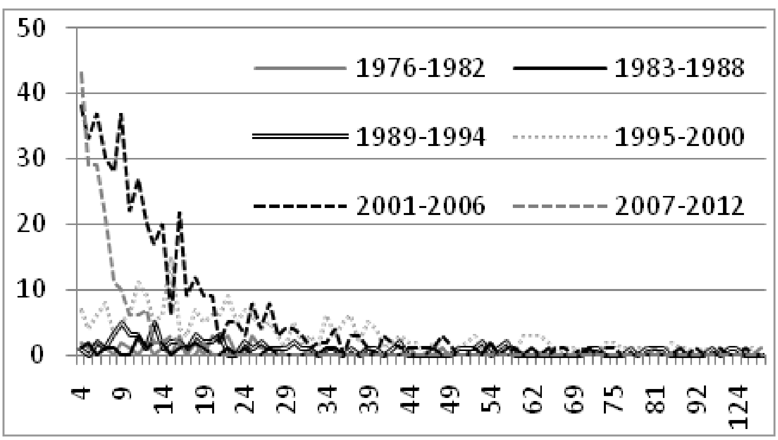
2 growing production of complex and specialised patents on behalf of partnerships (patents with a large number of backward citations).

Figure 11 Backward citations frequency for EV by periods (1976–2012)



Source: ibid

Figure 12 Forward citations frequency for EV by periods (1976–2012)



Source: ibid

Meanwhile, during the first three periods forward citations curves[53] have a relatively flat shape and a low level of citations. In contrast, during the period of 1995–2000, a heterogeneous ensemble of patents is cited. Patents from this period become building blocks useful in accelerating the inventive activity in following periods. The period of 2001–2006 shows a mode closer to the origin, but the right side of its curve, moves towards the left. This could be explained by explored knowledge areas novelty and inventive step specialisation in the following period. Finally, the last period (2007–2012) does not show a clear pattern due to recent formation. If we exclude this last period, backward citations help represent the complex network of patents interdependence, which would indicate that during the period of 1976–2012 patent thickets presence has grown.

6 Conclusions

In this section, we can summarise how patent thickets and agents diversity relationship change in the course of time regarding electric vehicles inventive step. The first stylised fact worth noting is that, as a result of inventive step, a more complex knowledge network has been created, this establishes the conditions for patent thickets generation.

In a first period 1976–1991, the knowledge network is incipient and relatively disconnected. A few research areas (technological classes) are explored by a small number of agents. Small inventive step is distributed more or less homogeneously among agents. Agents, mainly companies, NPEs and inventors, begin exploring relatively distant areas (cf. the diameter column[54] for this period in Table 1). A few large companies registered patents during this period. Given these conditions, patent thickets probability is low.

In the period 1992–2003, inventive step increases exponentially. The number of new agents in the system increases (from 12 new agents in 1992 to 270 in 2003, a total of 258 new agents during this period) simultaneously it tends towards progressive concentration of knowledge in a few agents. Research areas had quadrupled, from 336 classes in 1992 to 1,230 in 2003. The knowledge network is highly connected (the network diameter went from 4 to 3 from 1992 to 2003). Relevant research areas were beginning (mainly completely electric vehicles and hybrid vehicles).

If only these electric vehicles structural characteristics are considered, the probability of coming across patent thickets increases. However, this is not the only factor. Some other characteristics must be taken into account, such as agent attributes, for instance, NPE's motivations. NPE's contributes to the system with few patents, but these sensibly influence the inventive step trajectory: they possess a large number of forward citations. Likewise, it can be said that as long as public or private NPE's do not commercialise their technology, they are not motivated to obstruct technologic exploitation, but rather issuing licenses.[55]

In the period 2004–2012, exponential growth of inventive step continues. Likewise, and despite strong knowledge concentration, new agents enter in the system (333 in the period) and research areas increases (technological areas), but at a lesser rate (from 1,294 in 2004 to 2,394 in 2012). Contrary to the previous period, knowledge spreads hierarchically[56], increasing patent thickets probability, especially in densest and most nested areas, such as data processing. Inventive step moves from tangible content patents to intangible content (software), that is, intensive knowledge patents. Electric vehicle nature is transformed.

In this period, new participants regarding data processing entered to the inventive step, especially companies from electronic sector. Companies such as Google[57] may become electric vehicles producers, and that, from the point of view of intellectual property, may push traditional companies from the automotive industry to defensive positions. During this period, partnerships value grew with regard to the knowledge they provide to the system. By sharing the inventive property, partnerships allow their participants to reduce the patent thickets issue. Agents comprising a partnership would have fewer incentives to mutually block themselves. At the same time, partnerships expansion may increase the risk of patent thickets.

It is fundamental to include the agent's diversity in patent thickets studies, since, as in this case, it provides information and enriches the phenomenon understanding. This study established bases for a more precise theoretical analysis that allowed the examination of interaction between nature of good (electric vehicles), attributes of the agents, and rules. It also sought to refine and propose new analysis techniques for patent thickets.

Intellectual property concentration in a more reduced group of agents may result in different practices to solve the patent thicket problem typically, with litigation and cross-licensing.[58] But, in automotive industry, we has identified in addition:

1 buy the patent or payment of royalties

2 buy a company and its intellectual property rights

3 transfer ownership of the patent of an individual inventor to a company formed by himself

4 split a company and transfer its intellectual property to one of the resulting companies

5 transfer the patent from one company to another through a joint venture.

Finally, it is necessary to go deeper in the study of patent systems. It creates certainty in regard to intellectual property rights, as well as conditions that block innovation. A perspective incorporating institutional theory and complex systems theory, could provide good results both to represent and explain the phenomenon as well as to diagnose and develop proposals.

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Notes

1 A conventional vehicle has around 10,000 unique parts (Ulrich and Eppinger, 2009; Lara et al., 2006). It has five big subsystems (powertrain, chassis, safety, comfort and info-entertainment). Depending on the level of luxury it incorporates, from 30 to 100 micro-computers (Juliussen and Robinson, 2010). Furthermore, developing a new model takes three to five years [Bauer, (2007), p.278].

2 Among the different motors that have been developed, it is possible to identify:

   a pure electric

   b hybrid (soft, complete, parallel and serial)

   3 as well as fuel cell (Roland Berger Strategy Consultants, 2009).

3 Batteries can be classified in different types: starter or traction battery; or according to its active materials (acid lead, nickel metal hydride, lithium or air, etc.) (Pistoia, 2008; Lara and Salazar, 2013; Reyes, 2012; Flamand, 2016; Huth et al., 2013).

4 An electric vehicle's battery uses sophisticated energy management system (SAB), integrated by micro-computers, sensors, actuators and a cooling subsystem (Pistoia, 2008) optimising necessary electric power for traction and other vehicle functions.

5 Henceforth, they are called only 'inventors'.

6 Organisations linked to electric vehicle technological innovation are numerous. There are patent offices, governmental offices promoting or restricting technological change, consumers, non-governmental institutions and courts. We will focus only on the subset of agents linked exclusively to technological invention.

7 Even if the scope of this study is descriptive, when the evidence allows, we present reasonable inferences regarding the causal relations of our study variables, namely, the complexity of the inventive step of electric vehicles (represented by the network of technological classes) that is

associated with the diversity of agents (analysed with the distribution of patents among the agents) and the patent thicket problem (represented with the complementary measures of the technological classes distributions, citations and patents).

8 The other 'basics' are: aggregation, tagging, flows, nonlinearity, internal model and construction blocks. We focus on diversity, as it is our topic of interest.

9 For example, lithium battery has variations generating intra-type diversity according to active material used in its cathode: lithium-titanium, lithium-manganese, lithium-cobalt, etc. (Reyes, 2012).

10 For example, diversity between types can be observed in engines: internal combustion engines, electric engines or hydrogen engines.

11 Following the diversity causes at Page (2011) type, we know that:

a Mutation is a random change in an element state, for example, A_m technology could be [0, 0, 1, 0, 0] where the third element of technology A changed, so that A_m is a mutation of A.

b The inversion is the inverse change of the order of the elements, the inversion of technology A, A_i, is the same technology A, as [0, 0, 0, 0, 0] is the same technology as [0, 0, 0, 0, 0], but in the case of technology B, same effect does not happen, B inversion is [1, 1, 1, 0, 0] where the first element changes order with the last, the second with the second to last and so on, so that B_i is a variation of B.

c The recombination is present when two chains come across each other to form others, for example, A and B can recombine in their fourth element, meaning, the first four elements of A are combined with the last element of B and the first four elements of B combine with the fifth element of A, the resulting variations are: [0, 0, 0, 0, 1] and [0, 0, 1, 1, 0], where both resulting chains are a recombination of mother chains.

d Transference happens when one or some of the elements of a chain are transferred to the other, for example, the three first elements of A are transferred to B, the result is the [0, 0, 0, 1, 1] chain.

e Finally, representational diversity is simultaneous combination of the other causes.

12 In the six causes generating diversity among types underlies this same logic of selection but with its corresponding characteristics.

13 For example, electric vehicles battery requires, unlike conventional vehicles, a cooling system, microcomputers that manage the car's energy, sensors, specialised software, actuators, electronic monitoring systems, etc. (Pistoia, 2008).

14 For instance, during each electric vehicle development, a high, fast and reliable interconnectivity is required practically for all the vehicle subsystems (Juliussen and Robinson, 2010).

15 All patents are classified according to the technical knowledge area that they belong to. Each patent office has its own classification and an additional one belonging to the World Intellectual Property Organization (WIPO). Therefore, when referring to *the class*, we are indicating the technological domain that a patent belongs to.

16 There are several reasons for an agent registering a patent; these range from the protection of their knowledge to strategic reasons (Blind et al., 2006).

17 http://www.uspto.gov/web/patents/classification/international/est_concordance.htm (accessed 20 November 2012).

18 Cf. USPTO (http://www.uspto.gov/web/patents/classification/international/est_concordance.htm).

19 It is important to point out that these patents include all electric vehicles, meaning, not only those of the automotive industry but also therapeutic vehicles, such as electric wheelchairs or mountable electric vehicles for children. This type of vehicles is not removed from the analysis due to two reasons:

a basis would be compromised with different and subjective criterion to the one constructed b the possibility of observing possible relations between this type of products and the electric vehicles of the automotive industry.

The basis includes, in addition to the patent number, the following data: year in which the patent was assigned, year in which the patent was applied, number of forward citations, number of backward citations, number of investors, number of the patent, number of patent claims, country of origin, technological classes, number of technological classes and the number of inventors.

20 Patent classes can represent a particular knowledge contained in the patent, e.g., if a patent has the 340/455 class (*communications: electrical […] indicator responsive to a condition of the vehicle, battery charging systems*) and 701/22 class (*data processing: vehicles, navigation, and relative location; electric vehicle*) then invention is related to data processing in order to indicate the battery state or the vehicle state.

21 It was explained in the previous section that a technology may be represented by a binary chain of components (for example, T technology may be represented by chain [0, 1, 0, 1, 0]). In the case of patents, each patent is classified and according to their classification, a chain of classes representing a specific knowledge area is generated, instead of using the binary states 0 and 1, the key number of their classification is used, for example, patent number 4124086 has two technological classes, 180/65.1 and 310/219, so it forms the chain [180/65.1, 310/219] and patent 4364444 has five technological classes that could be represented through the chain [180/65.1, 165/104.34, 237/12.3A, 361/694, 454/75]. The longer the chain is, the more complex knowledge it contains, because it includes many areas of knowledge, while a shorter chain indicates that knowledge contained in requires fewer knowledge areas and the patent is therefore more generic.

22 For network construction details, see Appendix and for a deeper review regarding the meaning of these statistics, see Chávez and Lara (2016). In this same paper, the evolution of the knowledge structure for electric vehicles is explored, calculating the decrease of the entropy of the technological classes. Similar works calculate the technological sources between sectors and regions (Castaldi et al., 2015) under the notion of the related variety and although sources external to the sector is not the subject of this article, it is a field of prominent analysis for complex technologies.

23 Every patent is assigned to a person or organisation (assigner), guaranteeing the intellectual property rights in the country where the registration was made.

24 NPEs are organisations that have registered patents, but do not usually exploit the patented technology in the production of final goods. These are research centres, universities, governmental offices and law firms.

25 The claims describe in detail proprietors intellectual property rights. The number of claims gives an idea of the patented knowledge novelty.

26 All patents have references (citations) from another patent, so that a relation can be established between two patents through the citations. Said relation, could be forward when patent B is cited by patent A, or backward when the patent B cites patent A. Thus, when a patent cites other patents (backward citations), it means the knowledge being claimed has records in other patents. Whereas, a patent is cited (forward citation) means its knowledge has been background record or source of another patent knowledge.

27 A patent can have one or more classes, the more classes it has, the more technological domain its knowledge belongs to, therefore it is more complex.

28 Patents indicate the names and number of inventors participating in the knowledge development. Average inventors number indicates the research team average size generating a patent.

29 Most of the patents produced by partnerships are very recent and therefore not often cited.

30 The first is a horizontal specialisation (Giannitsis and Kager, 2009) known as Global Hybrid Cooperation comprised by BMW, Chrysler, Daimler and General Motors and the second is a vertical specialisation integrated by Toyota and Aisin, its subsidiary.

31 Mattel, a company in the toy industry and Invacare specialised in wheelchairs design.

32 Dedicated to infant care products manufacture. This company does not belong to the automotive industry.

33 The fact that Honda, despite being a leading company in the sector, does not make a many partnerships stands out. It has only two patents that were achieved in partnerships, one with The Regents of University of California in 2005, and another with The UWM Research Foundation in 2012.

34 Paice is a good example of intellectual property rights value regarding to electric vehicles. This research centre sued Toyota for illegally using knowledge patented by Paice. Toyota was infringing on the property rights of Paice with the *hybrid synergy drive system* of its vehicles Prius, Highlander, and Lexus RX400h. Texas District court ruled that Toyota had to pay royalties to Paice of 0.48%, 0.32%, and 0.26% (of its respective models) on the total price of each unit sold. See Paice LLC v. Toyota Motor Corp., No. 2:04-CV-211-DF, 2006 WL 2385139 (E.D. Tex. August 16, 2006).

35 The structure and interpretation of this network is the same and is derived from Figure 2. The shadows represent the density of the network of technological classes and the dots the classes in which the different agents patent (companies, partnerships, NPEs and inventors).

36 This is discussed in more detail further below.

37 The agents that first patented in the corresponding year are counted as new agents.

38 Although from 2002 to 2004, the entry of new agents decreased, the secular trend towards increase of new agents is nevertheless maintained.

39 As new inventors entry decreases. During the period of 1976–2012, approximately one new agent (0.96 new partnerships and 1.28 new NPEs) enters into partnerships and NPEs per year.

40 This is the quotient between the number of new classes accumulated and the number of patents accumulated by each type of agent.

41 In order to identify concentrated and diversified search patterns, the following steps were followed:

a Concentration coefficient was calculated for all agents regarding the classes, in this case, it is calculated the ratio that a particular class represents for a specific agent divided by the ratio that the same class represents in the whole industry for the chosen periods.

b Concentration indexes are sorted in order to obtain homogeneous ranges and then converted to natural numbers.

c The frequency of these values were calculated and graphed.

42 *Patent specification indicator:* Patents are described in accordance with the number of technological classes. A short chain refers to a general knowledge, a long chain to a specific one. The quantity of classes (length of a chain) describing a patent shows its specification.

Patent depth indicator: In the case of electric vehicles, USPTO groups its different classes hierarchically in eight levels: mainline, level 1, level 2, level 3, level 4, level 5, level 6 and level 7. A class with level 4 belongs to a level 3 and at the same time to a level 2 and so on. In this manner, the depth of the knowledge of a patent can be examined.

43 Table 4 was built in the following manner: rows specify the class longitude and columns depth according to the type of agent. How is Table 4 interpreted? Squares highlighted in medium grey are the mode (greater frequency) of combination of classes and depth. For example, in the first box (partnerships), number 25 is highlighted in medium grey colour. This means 25 patents of the partnerships have three classes and a depth level 2. Squares in light grey indicate the longitude mode of the classes and the depth for each type of agent. Squares in black identify the maximum degree of depth or specification employed by agents.

44 Probably, this is associated to the fact that partnerships are a relatively recent phenomenon (1995 onward), cf. Figure 8.

45 In fact, Patent 7969039, issued to Honda in 2011, has these two characteristics.

46 In our paper, Lorenz curve describes patents concentration level per agent. A uniform distribution of patents would describe a completely straight diagonal line, the further the curve moves away from this straight line the more concentrated the patents are in few agents.

47 This could be because of the low inventive activity in the period.

48 The complete list of the technological classes and their concepts are in [online] http://www.uspto.gov/web/patents/classification/selectnumwithtitle.htm (accessed 20 November 2012).

49 Advanced batteries design and development became the key during this period (Lara and Salazar, 2013; Reyes, 2012; Huth et al., 2013).

50 Bauer (2007), Juliussen and Robinson (2010) and Lara (2014).

51 Combining the number of claims and the number of patents through frequency distribution is a way of measuring. When frequency takes the form of a flat bell, the probability of overlapping patents is low. The higher the frequencies and the more their distributions take form of a single tail, the higher the probability of overlapping patents (IPO, 2011).

52 Its interpretation is relatively similar to claims frequency.

53 Forward citations show a similar behaviour to the backward citations, but out-of-step (considering a single period). This is due to the fact that the citation of a new patent is less probable than the citation of an older one.

54 The network diameter is the shortest distance to go from one point to another. In our case, it is an indicator of the closeness between knowledge.

55 This is the case even with patent trolls, a type of NPE that does not generate knowledge but acquires patents from other agents as any other financial asset for its subsequent licensing.

56 As a result, three central invention areas are configured and consolidated: hybrid vehicles, fully electric vehicles and data processing.

57 Although in the database used here – which goes from 1976 to 2012 – there are no patents from Google, in 2014 Google received two patents (8825391 and 8688306; containing class 701/22) meant for autonomous vehicles design.

58 Particularly, when both agents have a relatively large and complementary patent portfolio.

Appendix

The general steps that followed for the construction of the class network were:

a From the information system of the USPTO, technological classes 180/65.1, 180/65.21 and 701/22 were downloaded in patents from January 1, 1976 to November 20, 2012 by means of the search command ccl/180/65.1 or ccl/180/65.21 or ccl/701/22). The download was made from http://patft.uspto.gov/netahtml/PTO/search-adv.htm.

b All technological classes were extracted and ordered in a new base maintaining the corresponding patent numbers.

c With the data of said base, the adjacency matrix of the classes related to the patent was constructed. That is, for each pair of classes, a link is assigned if a patent contained said pair of classes.

d This matrix was introduced in the NodeXL network analysis program, attaching a column specifying the year that was first patented in each class.

e The network and its statisticians were generated in the same program for further analysis.