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Putting Complexity to Use: Distinguishing Low-Emission Vehicles (LEVs) as Environmental Technology in Patent Data

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Abstract

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Abstract: In the face of a global ecological crisis, the automotive industry is increasingly under pressure to produce more sustainable options for their customers. As road transport accounts for 16 percent of human CO2-emissions, several attempts have already been made to implement cleaner technologies. Low Emission Vehicles (LEVs) are possibly part of a sustainable future, but there is no widely accepted agreement in the literature as to what constitutes such technologies (Oltra, Kemp, & de Vries, 2010). Part of this problem lies in the complexity of innovations and their changing technological compositions over time. Instead of problematizing this complexity, this paper aims to explore how vehicle manufacturers and LEV solutions are part of the broader field of vehicle design by embracing the complexity of sub-activities that constitute such technologies.

Based on the notion of technological relatedness, patent data is used to map the technological landscape, from which the patent activity of firms involved could 1) indicate a more thorough idea of patent portfolios, 2) leave more room for analysis of their evolution 3) enable the placement of the specialization concept properly within the firm?s patenting activity as a whole and 4) highlight regional differences. The methodology uses co-occurrence of technological

classifications to map the network of vehicle design in general cf. Hidalgo et al (2007). Subsequently, different centrality indicators are calculated and then composed into one index. Comparison of the composed indices for the network as a whole and subsets can be used to map the (changing) patent-portfolios of firms and technologies. The dataset will consist of all patents that return on specified queries and were filed by any of the 24 largest car manufacturers between 1990 and 2010. In total about one million patents are included.

Preliminary results indicate that Europe?s largest manufacturers seem not to be active in patenting technologies that can be classified as ?Electric equipment of propulsion of EVs?. Neither is Ford nor GM. However, this activity is a very important node in the development of both hybrid and electrical solutions. Preliminary findings suggest that lacking the in-house capacity to produce such technologies may result in a competitive disadvantage in the future. Supposedly, the typical Japanese Toyota-business model of large industrial conglomerates producing a variety of related products may be advantageous. The vertical disintegration of mainly European companies may induce innovative behavior among suppliers that eventually spills over, but it can have an important drawback for creating competitive advantages over time. Furthermore, particularly Fuel Cell Vehicle (FCV) development seem to be positioned at the periphery of vehicle design and is composed of a limited set of activities. That may suggest that FCV-technology is still mainly concerned with developing solutions to structural problems of implementing this rather new technology into vehicle design. Perhaps, if key problems are resolved in the near future, Fuel Cell technology may become a more serious candidate but the competitive advantage shifts from technological characteristics to infrastructure advantages. So far, it seems that hybrid vehicles are the most logical alternative in the near future and they are likely to be produced by Japanese firms.

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Putting complexity to use:

Distinguishing Low-Emission Vehicles (LEVs) as Environmental Innovation in Patent Data

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Abstract: The complexity of innovations is perceived to prevent a justifiable demarcation of such innovations. This paper, however, aims to propose a methodology for demarcating patent activity and innovation strategies among car manufacturers in their search for Low-Emission Vehicles (LEV's) by using comparative network analysis. The results show that European manufacturers aim for a broad strategic scope of patenting activities in contrast to a more specialized pattern among Asian car makers. Strategically however, even though conventional technology remains to be important a process of hybridisation seems to occur, which could turn out to be advantageous for Asian and American manufacturers.

Keywords: complexity, patent data, network analysis, Low Emission Vehicles, environmental innovation, relatedness.

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1. Introduction

In the face of a global ecological crisis, the automotive industry is increasingly under pressure to produce more sustainable solutions. Despite technological progress, 96% of automotive vehicles around the world are still powered by fossil fuels. Although the exact origins of the first automobile are ambiguous, the gasoline-powered version originates from the 1870s and though the design has improved ever since, the core idea to use gasoline or diesel combustion to power a vehicle remains the same. Though oil-supplies are limited, the polluting nature of automotive mobility may be even more problematic. As road transport accounts for 16 percent of human CO_2-emissions, several attempts have already been made to implement cleaner technologies (OICA, 2011). California for instance played a leading role in the US by implementing the clean air act in 1990. Furthermore, the Obama administration announced exhaust emission limitations and also made millions of dollars available for more sustainable solutions (Dicken, 2011). Moreover it is rumoured that these sustainability ambitions have influenced the TARP-negotiations with the biggest three American car-producers halfway 2009 (Financial Post, 2009). Evidently, the automotive industry is increasingly under pressure to produce more sustainable options to their customers (Ernst & Young, 2010).

Although alternative energy-sources have been researched as viable solutions for reducing the carbon-lock in, car technology itself has relatively recently been changing towards cleaner developments on a substantial scale. In the early 1990s, electric vehicles (EVs) have been put forward as distinct competitor for internal combustion engine vehicles (ICEVs). Since developments to overcome functional limitations of such designs have stagnated, several other technologies were explored that may yield satisfactory results, of which most notably fuel cell vehicles (FCVs) and hybrid vehicles (HVs). The essential characteristic of these types of Low Emission Vehicles (LEVs) is a drive-train that is not (exclusively) powered by fossil fuels. Nevertheless, a multitude of innovations has occurred in the design of both ICEVs and diesel engines vehicles (DEVs) that has resulted in a more efficient use of fuel. So the spectrum of technological solutions spans at least five different designs: clean ICEV- and DEV-solutions as gradual improvement of existing technologies; and EV, HV and FCV as alternative and ‘radical’ new designs. The main advantages of developed solutions based on ICE or DE are twofold. First, as the technology is more mature, more knowledge on the design has been accumulated among producers, which could make it easier to improve. A second major advantage is the reliance upon existing infrastructure which might create a competitive advantage for firms specialized in ICE or DE technologies (Oltra & Saint-Jean, 2009).

So, on the one hand, there are existing technologic solutions in which manufacturers are locked-in, but are still incrementally improved under changing selection forces. On the other, a heterogeneous set of alternatives is emerging that has not converged yet to a final design. So, where is this heading towards? This paper aims *to explore how* *vehicle manufacturers and LEV solutions are part of the broader field of vehicle design and to how to distinguish firms and sustainable solutions within the wide variety of activities*. In order to do so, the relevant literature and concepts will be discussed in the following section. Then, both data and methodology will be covered in section Three, followed by the results of the analyses in section Four. Section Five will summarize the conclusions and section Six provides some possible extensions for future research.

2.Theoretical background

2.1 LEV as environmental technology

Although the literature on sustainable innovations is abundant, relatively little has been written about the particular case of LEV design. One attempt is provided by Oltra and Saint Jean (2009) who analyze competition between the different LEV technologies, and found that the investigated patent portfolios of firms confirm the dominance of ICEV and diesel vehicles, but that hybridization is becoming increasingly important (p. 210). Similarly, Frenken, Hekkert & Godfroij (2004) notice an increasing variety in patent activity combined with a re-orientation from Fuel Cell Vehicles to Electric Vehicles and Hybrid solutions (p. 504). These conclusions emphasis the relative importance of knowledge spill-overs in shaping new solutions, as hybrid vehicles incorporate both a combustion engine and an alternatively powered engine. Competences in ICEV or diesel engine production are in that sense myopic to the skill portfolio needed to produce hybrid solutions. More importantly, the importance of spill-overs and relatedness is further strengthened by the complex nature of the technologies investigated. Yet, the critical question how technological trajectories, knowledge relatedness and firm activities are intertwined in LEV development remains unanswered.

Finally, a paradox concerning these issues is seemingly apparent. Mitsubishi is the highest ranked car manufacturer by the amount of cited patents in fuel-cell technologies, which indicates this firm’s relative importance (Verspagen, 2007, p. 108). On the other hand, Mitsubishi is considered to be highly *unspecialized* in FCV-technologies (Oltra and Saint-Jean, 2009; p. 208). Hence, “*The problem is that patent classification systems do not provide specific categories which cover environmental patents and there is also no widely accepted agreement in the literature as to what constitutes an environmental technology* (Oltra, Kemp, & de Vries, 2010, p. 143)” Part of this problem lies in the complexity of environmental technologies, such as LEVs which therefore fall in multiple categories of the classification system. The empirical findings above have shown that complexity – in this case of technological activities that may or may not be combined in various ways over time – is highly incompatible with the hierarchical nature of IPC or ECLA classifications. An ex-ante defined ‘specific category’ as mentioned by Oltra, Kemp & de Vries (2010) could therefore turn out to be an ambiguous and/or superficial solution. Instead of problematizing this complexity, the relatedness of sub-activities that constitute such technologies can be used to discern them; subsequently providing insights into the strategic position of firms and their investments in patent portfolios.

2.2 Knowledge relatedness in technological trajectories

Economic activity is more and more believed to be a function of knowledge creation or the capacity to absorb information. The growing importance of knowledge related dynamics has led to an increasing emphasis on complexity and interrelations but also polarized the conceptualization of different externalities and their functional role in economic systems (Arthur, 1989). Basically, a strengthened notion of interdependency implies the existence of systematic feedback mechanisms that are reflected in the importance of externalities and shape economic dynamics (Kirman, 2004). The inclusion of such feedback has diverged the so-called heterodox approaches from classical thinking in the refutation of the latter's assumption of constant returns to scale (Jovanovic, 2003; Plummer & Sheppard, 2006). Furthermore, as the *accumulation* of knowledge tends to be myopic in a spatial or relational sense, path-dependency (Arthur, 1989; Kemp, Rip, & Schot, 2001), path creation (Garud & Karnøe, 2001; Schienstock, 2007) and technological trajectories (Dosi, 1982; Verspagen, 2007) become almost synonymous with economic growth and development.

Nevertheless, some of these externalities are more prominent than others in different phases of the industry life-cycle (Klepper, 1997; Neffke et al, 2010). Mature industries such as those specialized in ICEV's, are less susceptible to information externalities since their focus is generally on the exploitation of a technological design, while scale economies in production have a higher strategic importance. Emerging technologies, such as the different LEV-designs, are often a source of technological relatedness that created the opportunity for innovative solutions to existing problems. Learning-by-doing and information externalities are then to be seen as decisive factors in the evolution of new industries, while the absence of any standard alternative prevents the occurrence of scale-economies (Anderson & Tushman, 1990).

A profitable starting point to understanding the different composition of and competition between LEV technologies would then start with conceptualizing the (core) competences of the firm and the landscape they operate on *based on the notion of technological relatedness.* Are the alternative solutions to the combustion engine really (core) competences based on which manufacturers compete? Although different fields of technologies might portray different patenting strategies, a network lay-out of the patenting landscape as infrastructure for activity to take place is the essence. From this particular landscape, the patent activity of the firms involved could 1) indicate a more thorough idea of the patent portfolio, 2) leaves more room for analysis of its evolution 3) enables the placement of specialization concept properly within the firm's patenting activity as a whole and 4) highlight regional differences.

2.3 Measuring interrelatedness in LEV-patents

Research in relatedness – or the opposing concept of diversity or variety – provides a broad range of conceptualizations and methodologies for measurement. In its simplest form, diversity can be measured with entropy statistics that are common in physics. The most often type of entropy measurement is the Shannon-entropy that is related to the information content of a probability distribution (Frenken, 2004; Mitchell, 2009). In its application, it is often used as a measurement for diversification, where a value of 1 means totally clustered and 0 means equally spread. In patenting practice, entropic measurement can assess the evolution of variety among firms or technologies (Frenken, Hekkert, & Godfroij, 2004). A considerable downside of such measures of diversity is that it can only be used in combination with an ex-ante defined and hierarchical classification. In case of Frenken, Hekkert and Godfroij (2004) the characteristics on which the classification of technologies was based remains uncertain. Another method that seems more appropriate is to define the entropy according to a pre-existing classification (Frenken, van Oort, & Verburg, 2007; Boschma, Eriksson, & Lindgren, 2009). While this method may be less suggestive, it is restricted by the initial classification in the sense that it cannot integrate relatedness *among* classes that may be relevant. That would imply that a method based on co-occurrence would be the most likely variant of measuring relatedness.

The basic foundation of such methods has been initially proposed by Engelsman and van Raan (1994), but has been vastly extended Neffke and Svensson Henning (2008). Their focus on industry relatedness leads to correcting simple co-occurrences for class specific characteristics. Some critical difference occurs however in applying this idea to the case of patenting LEV technologies. A first difference to note is that this paper focuses exclusively on car manufacturers, whereas the main reason for the extensive corrections made is due to the broad range of industrial activities. Hence intra-sectorial differences in patenting that need to be corrected for do not occur. Secondly, firms sometimes file few patents that are not part of their core competence to secure intellectual property that may yield benefits in the future (Blind et al, 2006; OECD 2009). As these activities are marginal, econometric estimations of observed linkages between patent classifications will most likely incorrectly model these activities; extensive corrections could distort the role of important strategic patents. So even though the method proposed by Neffke and Svensson Henning (2008) is the most complete measure to date, it seems less desired in the case of LEV-patenting.

The option left that captures revealed relatedness has been proposed by Hidalgo et al (2007). As will become evident in the methodology section, the method reasons from a rather pure concept of revealdness and is also able to incorporate some corrections, without over-theorizing. Most importantly, while it may not deal with entity-specific reasons for asymmetries extensively, it is able to include strategic patenting as well, which makes it the most suitable option. As the next section will prove, to a large extent this methodology has been used, but it may deviate on certain aspects. These deviations are mainly due to the differences between measuring industry relatedness for which it was originally used (Hidalgo, Klinger, Barabási, & Hausmann, 2007; Haussman & Klinger, 2007) and this paper's interest in firm activities measured through patenting.

The use of patent-data is not unambiguous, neither are the choices made in this paper.

Selecting relevant patents remains an issue. A broad query like ‘vehicle’ includes a wide variety of types of vehicle. For instance, most categories starting with B62 are (motor) cycle related and the vast majority has been filed by Honda. It may be acceptable that the future of sustainable transport includes such types of transport. Even though such ex-ante theorizing would better be avoided, it does raise the same arguments on which Neffke and Svensson Henning base their extension. However, that would shift the debate to the conceptual meaning of revealed and related, which may require different arguments when applied to patent data instead of industrial production data.

3. Data and Methodology

3.1 Data

The empirical data used in this paper stems from the European Patent Office’s (EPO) PATSTAT database. A combined query of words and years has been used to retrieve the patents. To develop a picture of vehicle-design in general, all patents filed by the 24 largest car manufacturers that resulted for a query ‘vehicle’ in either title or abstract in the period 1990-2010 were collected. As data for 2009 and 2010 has not been fully updated, the analysis will be limited to the period 1990-2010. Furthermore, 9 firms were omitted due to the small number of patents included, leaving the 15 firms included. These are the 15 largest car manufacturers by production and account for approximately 90% of the total yearly motor vehicle production between 1998-2008 (OICA 2011). All patents were extracted by manufacturer on a yearly basis accounting for 102,000 patents. In addition, all results for the search-terms “Internal Combustion Engine Vehicle,” (11,000 patents) “Diesel Engine Vehicle,” (2,000 patents),”Hybrid Vehicle,” (9,000 patents) and “Fuel Cell Vehicle” (2,500 patents) were collected for the same years.

3.2 Methodology

Portraying the “patent landscape” as network of interrelations starts with the observation that patents are categorized according to their technology in the IPC classification system. In the case of (low emission) vehicles, the complex nature of the technology often results in multiple classification listings on the same patent. As explained before, the hierarchical organization of the IPC classification will therefore be insufficient to identify relatedness. Therefore, the methodology presented here in principal revolves around the argument that the more two patent groups occur *together* on a single patent; the closer these categories are technologically related. Therefore, to understand the scope of patenting that defines technologies or firm-activities, the IPC-classification is used to construct the patent-landscape. As most patents are assigned multiple classes, this landscape essentially concerns the pair-wise co-occurrence of classes on a single patent. Extending into all possible pair-wise occurrences will create an n-dimensional space where patenting takes place, where n is defined by all relevant groups, classes, subclasses or groups, depending on the desired detail. This research makes use of the fourth level (group), which entails enough detail without generating a too large landscape that is impossible to analyze. A typical example is for instance H01M8, where Section H is defined as ‘Electricity’, Class H01 as ‘Basic electric elements’ and

Subclass H01M as ‘Processes or means for the direct conversion of chemical into electrical energy’ and finally H01M8 as Fuel cells; the manufacture thereof. Subsequent Subgroups encompass specific features of fuel cell systems that may be relevant, but provide too much detail.

3.2.1 Manufacturer’s scope of activities

All patents that returned on the query ‘vehicle’ resulted in co-occurrences over 3083 different groups. Based on these co-occurrences, part of the argument provided by (Haussman & Klinger, 2007) was used. Let

$$P(c_i \cap c_j) \tag{1}$$

denote the joint probability of a patent to enlist both group c_i and c_j. Although it seems a logical measure, it is not normalized for the size of patent activity. If two categories co-occur exclusively with one another, but only on few patents in the sample, the distance between those classes is close in reality, but the probability measurement is low. In such case, the measurement would be off. Therefore, the *conditional* probability:

$$P(c_i | c_j) \tag{2}$$

seems more accurate. Yet, this crude probability does not account for the direction of relations. The chance of c_i given c_j may differ substantially from the probability of c_j occurring when c_i is given. For instance, chemical and physical processes may be closely linked to the development of fuel cells; while in contrast the development of fuel cells does not only cover chemical or physical processes. To account for this asymmetry, the best way to conceptualize the distance between two patent groups (δ_{ij}) seems to be:

$$\delta_{ij} = \min\{P(c_i | c_j), P(c_j | c_i)\} \tag{3}$$

Based on these distances, a symmetric adjacency-matrix M_δ can then be constructed that contains all 3083× 3083 possible pair-wise distances between patent-groups.

In the subsequent step, this paper deviates from the method proposed by Haussman & Klinger (2007) as it *does* include marginal activities. Hence, the Revealed Comparative Advantage of manufacturers in specific patent groups is not used as threshold for inclusion, or more formally:

$$\forall\, RCA_{mi}: \delta_{ij} \in M_\partial \tag{4}$$

As explained before, marginal patenting activities may prove beneficial in the future and are thus taken into account. However, the RCA as an index of specialization in particular patent groups is calculated to discern the activity of different manufacturers m, following Balassa’s (1961) definition in a similar argument as provided by Debackere et al (1999):

$$RCA_{mi} = \frac{c_{mi} / \sum_i c_{mi}}{\sum_m c_{mi} / \sum_i \sum_m c_{mi}} \tag{5}$$

As such, any RCA>1 means that a firm is specialized in filing patents in a particular group which indicates that the corresponding activities are part of the manufacturer’s main activities. Hence, it maps the patent portfolio of firms involved in a more robust method, while including the complex nature of technologies.

3.2.2 Distinguishing different environmental technologies

A next step involves discriminating ICEV-technology, DEV-technology, HV-technology and FCV-technology as a function of revealed group co-occurrence. For this purpose, a Composed Classification Centrality Index (CCCI) has been calculated for each patent group c_i as part of the vehicle patent landscape as a whole, for which the subscript N is used (CCCI_N). This measurement is an indicator of how central patent groups are in vehicle design as a whole. Subsequently, the relative importance of patent-groups in ICEV, DEV, HV and FCV is calculated similarly. If a patent groups has a higher centrality indicator in a particular technology (CCCI_T) than in vehicle design as a whole (CCCI_N), it is a part of that particular technology. All the activities that these groups correspond to and for which $\text{CCCI}_\text{T} > \text{CCCI}_\text{N}$ form the environmental technology subscript T refers to.

Based on Hanneman & Riddle (2005), one measurement for each centrality dimension [degree $e(c_i)$, betweenness $b(c_i)$ and closeness $c(c_i)$] were chosen. Degree-centrality was calculated using Bonacich's (1987) approach, in which the centrality e of unit i for a symmetric square matrix is expressed as:

$$e\,(c_i) = \frac{\sum_j \delta_{ij}\, e(c_j)}{\lambda} \qquad (6)$$

where λ is the associated eigenvalue (Bonacich, 1987; Borgatti, 1995). Additionally, the betweenness of a vertex c_i is defined as the fraction of shortest paths between any two nodes c_p, c_q that pass through c_i :

$$b(c_i) = \sum\nolimits_{c_p \neq c_q \neq c_i} \frac{\sigma_{c_p c_q}\,(c_i)}{\sigma_{c_p c_q}} \qquad (7)$$

The final element for the calculation of CCCI_N concerns a measurement of closeness, which is the inversed geodesic distance Δ_{ij} between c_i and c_{-i}, which is then normalized (Kilkenny, 2005). In concise form:

$$c(c_i) = \left[\frac{\sum^N \Delta_{ij}}{N-1}\right]^{-1} \qquad (8)$$

These three measurements of relative importance in vehicle patenting are then used as inputs for a Principle Component Analysis. Only one component was extracted that is used as a one dimensional variable following a Z-distribution. This variable is the composed centrality measurement CCCI_{Ni}, which because of its mathematical properties can compare vertices in a comprehensive way.

Subsequently, the relative importance of patent groups in the different technological solutions is mapped using technological specific queries [cf. Oltra & Saint-Jean (2009)] and following the same procedure as formalized in equations (3) and (6-8). Each node i has therefore a total of five CCCN values, one for the general (vehicle) network (CCCI_{Ni}) and an additional four (CCCI_{Ti}) to distinguish their relative importance in different technological solutions, where T indicates the specified technology. Comparing the composed centrality of the network as a whole with a similar measurement over a technology-specific network is the method used to discriminate environmental innovations by the scope of patent classes that *technologies* span. Yet, a simple threshold needs to be imposed as a technology's CCCI covers a different range than the network's CCCI. Hence, a dummy t_{iNT} was calculated in order to distinguish whether a node is an important part of ICEV/DE/HV or FCV technology, according to:

$$t_{iNT} = \begin{cases} 1 & if\, CCCI_{Ti} > CCCI_{Ni} \,\&\, CCCI_{Ti} > 0 \\ 0 & otherwise \end{cases} \tag{9}$$

Conclusively, if a patent group is more central in particular technologies in comparison to vehicle patenting as a whole, it can be classified as a core activity in the development of technological specific solutions.

4. Results

As in many other patent studies, the total amount of patents found dramatically increases for the LEV case too (Figure 1). More interestingly, however, is the distribution of amount of patent groups mentioned per patent for the different manufacturers and technologies (Figures 2 and 3). This gives an initial insight in the degree of integration of the solutions patented. With caution, the number of patent groups per patent is an indicator for the complexity or degree of integration of technologies. The more IPC-codes mentioned the more complex or wide ranging the technology.

In relation to manufacturers, European car producers – FIAT, Renault and BMW – seem patent less complex technologies than their Asian and American counterparts (Figure 2). The position of DaimlerChrysler is in this respect slightly problematic as German-American merger. Firm size does not have any apparent effect; while Ford and Hyundai-Kia as relative large manufacturers patent more simple technologies and Mazda for instance the contrary. In terms of the technological complexity, Figure 3 indicates that the new Hybrid and Fuel Cell technologies are similarly complex, while only diesel technology being significantly less.

To get a more comprehensive idea on especially the firm activities, Table 1 indicates the 25 most central nodes in the vehicle patent-landscape, i.e. the 25 patent groups with the highest $CCCI_{Ni}$. What is immediately apparent is the dominant position European firms in general and German manufacturers specifically have in patenting core technologies, both in terms of scale and scope.

Daimler, Volkswagen and Renault hold substantially more important nodes centrally in the network, which means they have a larger comparative advantage over a broad range of patent groups. Whereas most manufacturers are active in the centrally located patent groups, again the German firms have persistently a RCA greater than 1 in the most central five. Mazda and Hyundai are also strongly present in patenting these core technologies, but not as distinct.

Figure 1: Total number of patents per year

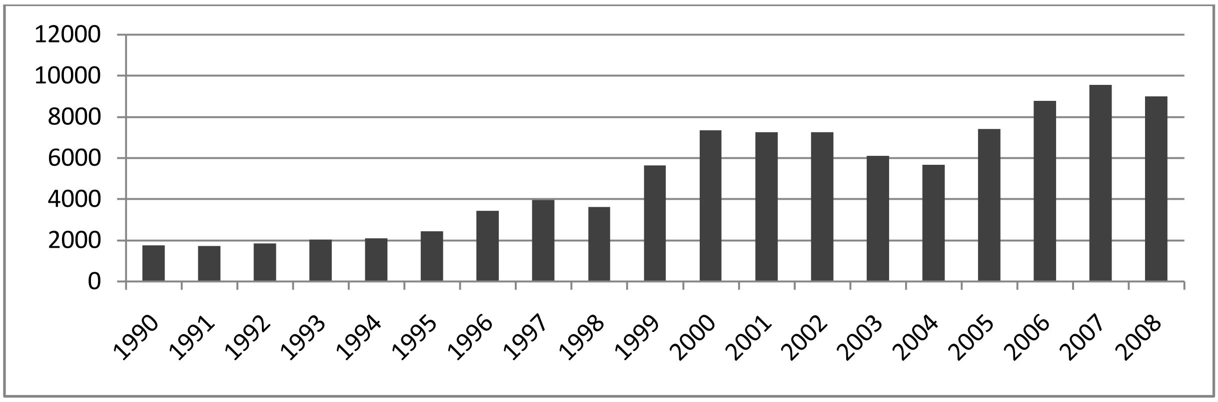


Figure 2: Amount of IPC-groups on patents per manufacturer

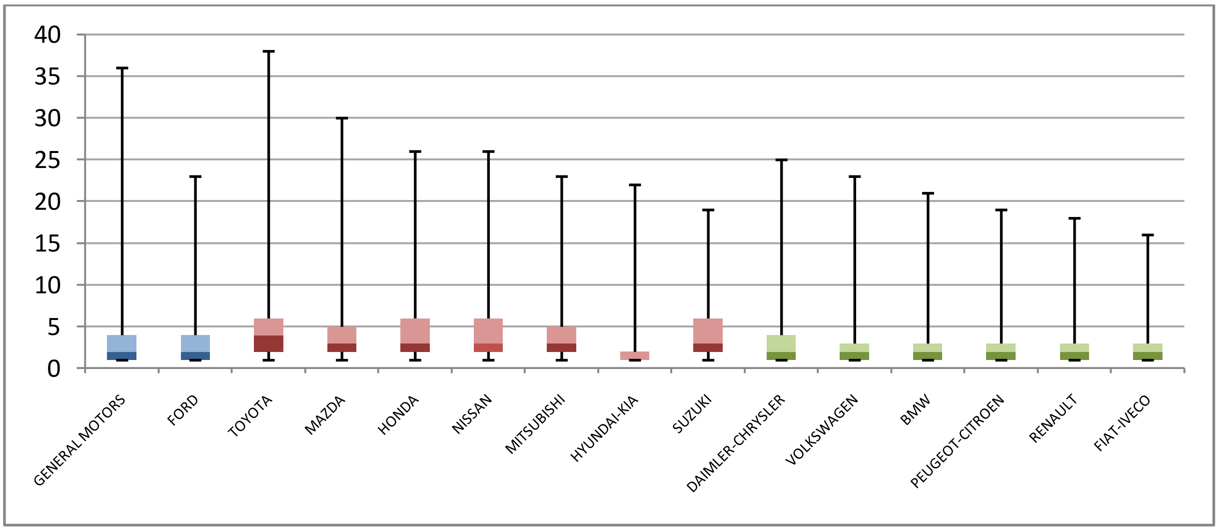


Figure 3: Amount of IPC-groups on patents per technology

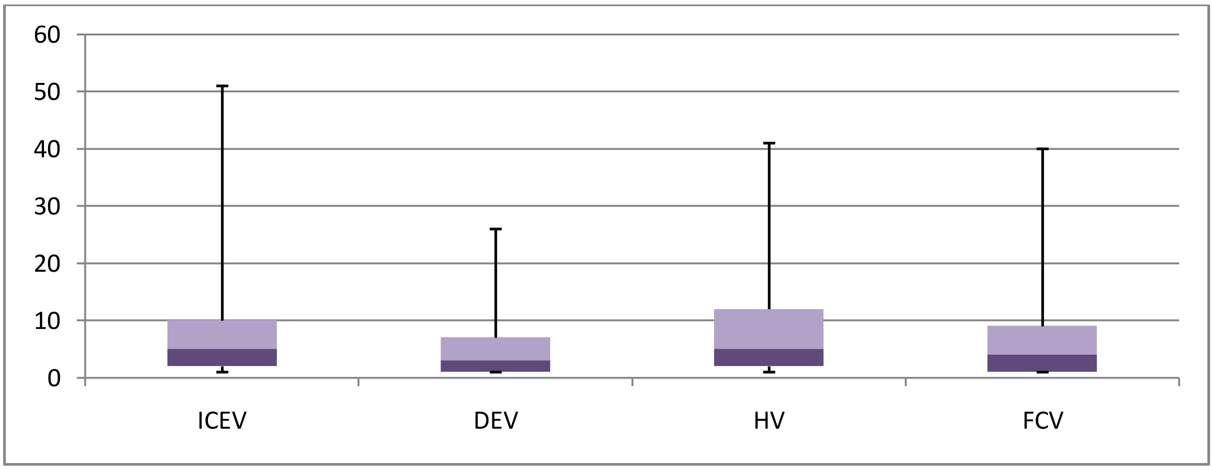


Table 1: Revealed Competitive Advantage in the 25 most central patent groups

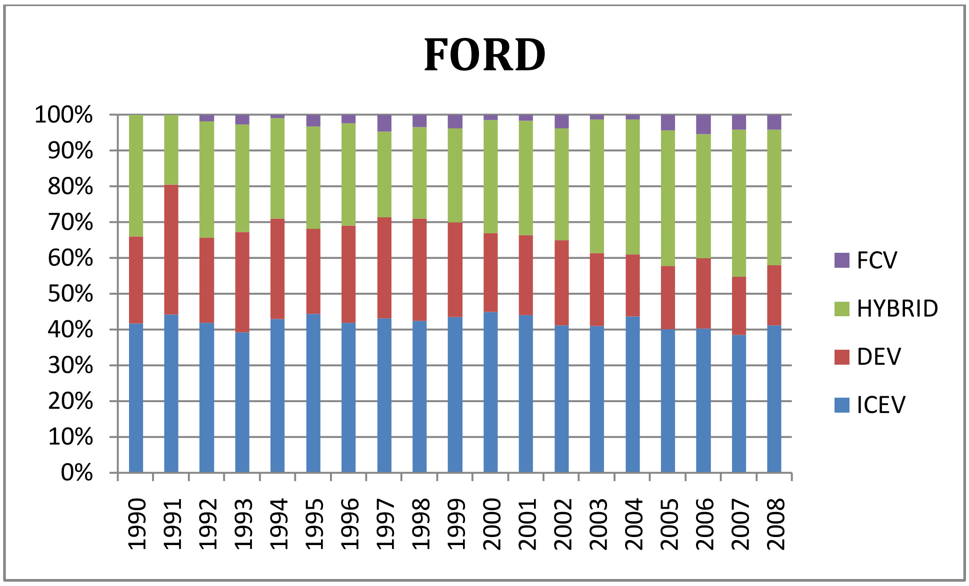
NODE	$CCCI_{Ni}$	GM	FORD	TOYOTA	MAZDA	HONDA	NISSAN	MITSUBISHI	HYUNDAI	SUZUKI	DAIMLER	VW	BMW	PSA	RENAULT	FIAT
B60R21	3.450	**1.18**	**1.33**	**1.06**	**1.64**	0.75	0.91	0.82	0.70	0.23	**1.09**	**1.86**	**1.16**	0.54	0.56	0.35
B60R16	3.358	0.46	0.93	0.69	**1.05**	0.63	0.41	**1.22**	0.97	0.40	**1.34**	**2.06**	**1.87**	0.93	0.84	0.57
B62D65	2.989	0.95	0.39	0.11	**1.35**	0.68	0.78	0.26	**2.36**	0.08	0.91	**1.01**	0.75	**3.29**	**1.84**	0.73
B60H1	2.932	**1.18**	0.89	0.54	**1.01**	0.32	0.48	**1.04**	**1.36**	0.52	**1.66**	**1.16**	**1.42**	0.90	**1.56**	**2.63**
B62D25	2.519	0.43	0.57	0.45	**1.88**	0.61	0.89	0.85	**2.27**	**2.11**	**1.06**	**1.03**	0.96	**1.34**	**1.13**	0.54
B60N2	2.220	**1.03**	0.76	0.71	**1.82**	0.55	0.53	0.23	**1.13**	0.97	**1.46**	**1.41**	**1.14**	**1.45**	**1.76**	**1.73**
B60K15	2.040	**1.29**	**1.14**	0.59	0.77	0.93	0.34	0.44	**2.27**	0.76	0.77	0.76	**1.92**	0.81	0.51	**1.24**
B60Q1	2.036	0.90	0.97	0.28	0.48	0.84	0.65	0.41	**1.07**	0.41	**1.38**	**2.34**	**1.58**	**1.50**	0.55	**1.14**
B60R13	1.858	0.73	0.75	0.43	0.65	0.60	0.73	0.32	0.85	**1.18**	**1.56**	**2.01**	**1.52**	**1.76**	**1.75**	0.75
H01M8	1.747	**2.05**	0.61	**1.75**	0.00	**1.17**	**1.48**	0.14	0.82	0.38	0.76	0.59	0.54	0.38	**2.15**	0.00
B60R11	1.619	0.19	0.82	0.22	0.95	0.53	0.58	**1.37**	**1.09**	0.80	**1.88**	**1.99**	**1.26**	**1.16**	**1.15**	**1.37**
B60L11	1.567	0.62	0.74	**2.59**	0.19	**1.51**	**1.58**	0.68	0.61	**2.29**	0.27	0.09	0.20	0.44	0.73	0.26
F01N3	1.530	0.61	**2.05**	0.98	0.53	0.37	0.72	0.54	0.78	0.55	0.86	**1.11**	0.64	**3.13**	**1.98**	0.85
G08G1	1.334	0.63	0.38	**1.30**	**1.15**	**1.08**	**1.55**	**2.29**	0.57	0.26	**1.21**	**1.00**	0.72	0.24	0.49	0.59
F02D41	1.307	0.97	**2.08**	**1.21**	0.80	0.82	0.92	**1.13**	**1.00**	0.71	0.55	0.55	0.68	**1.46**	**1.45**	0.72
B60K6	1.305	0.62	**1.08**	**2.46**	0.08	**1.46**	**1.49**	0.43	0.33	**2.75**	0.29	0.26	0.32	0.75	**1.17**	0.36
B60S1	1.276	0.37	0.45	0.17	0.03	0.29	0.55	0.19	**2.03**	0.00	**1.15**	**2.70**	**1.19**	**3.00**	**1.19**	0.55
B60N3	1.250	0.27	0.90	0.11	0.94	0.48	0.43	0.06	**2.09**	0.99	**1.58**	**1.71**	**1.51**	**1.21**	**1.71**	0.62
B60J5	1.238	**1.15**	0.93	0.39	**1.71**	0.58	0.42	0.41	**3.04**	0.71	0.72	0.66	0.64	**1.91**	**1.19**	0.60
G01M17	1.201	**1.80**	**1.63**	0.52	0.57	**1.11**	0.39	0.58	**1.67**	0.00	**1.04**	**1.16**	**1.26**	0.50	0.37	0.89
B60R25	1.200	**1.11**	0.75	0.72	0.85	**1.44**	0.72	**1.01**	**1.10**	0.53	**1.17**	**1.25**	**1.32**	0.50	0.47	0.46
B62D1	1.156	**1.85**	0.50	0.46	**1.22**	0.60	0.61	0.51	**1.52**	0.85	**2.05**	0.82	0.75	**1.47**	0.67	0.55
F16H61	1.138	0.82	0.77	**1.52**	**1.48**	**1.03**	**1.81**	**1.04**	**1.35**	**1.01**	0.49	0.55	0.41	0.34	0.90	**1.21**
B60W10	1.129	0.68	**1.18**	**2.33**	0.70	**1.12**	**2.00**	0.65	0.27	**1.52**	0.40	0.39	0.53	0.33	**1.02**	0.71
B60K1	1.113	**2.79**	**1.09**	**2.19**	0.17	**1.33**	**1.44**	0.77	0.23	**1.40**	0.47	0.16	0.42	0.39	0.93	0.43
RCA > 1		***10***	***8***	***9***	***10***	***9***	***7***	***7***	***15***	***7***	***14***	***15***	***12***	***12***	***14***	***6***

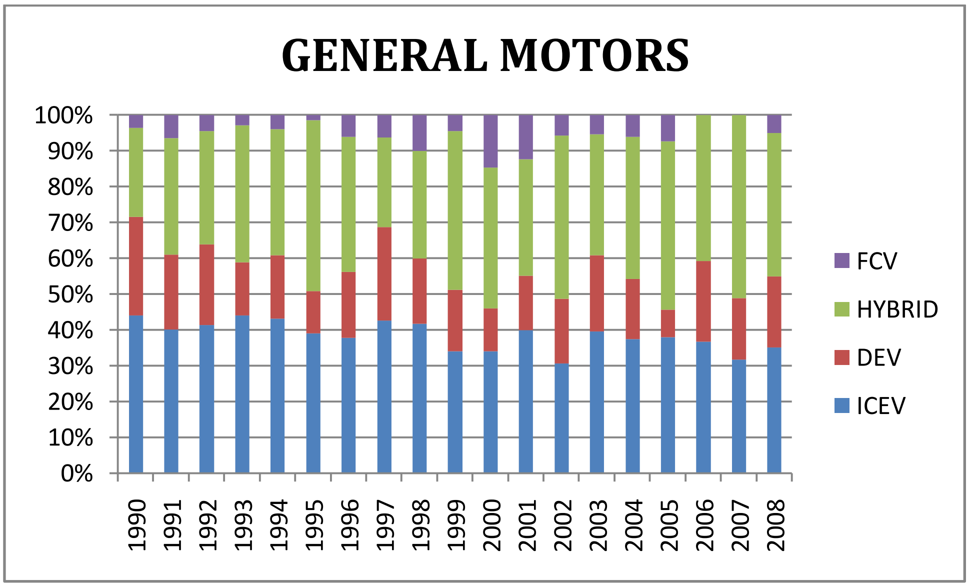
In terms of specialization in all 3083 patent groups, DaimlerChrysler, Volkswagen and BMW are the most diverse – or least specialized – vehicle manufacturers. Suzuki on the other hand is the most specialized manufacturer, with a distinct large RCA in non-central groups like fluid dynamics, fluid separation, ignition and piston design. In particular these non-central groups and activities are characteristic to any manufacturer's specializations. The mid-range between specializations versus diversification is occupied by Peugeot-Citroën and the smaller Asian manufacturers Hyundai-Kia and Mitsubishi. Ford and GM as well as Renault can be characterized as more focused in terms of activities.

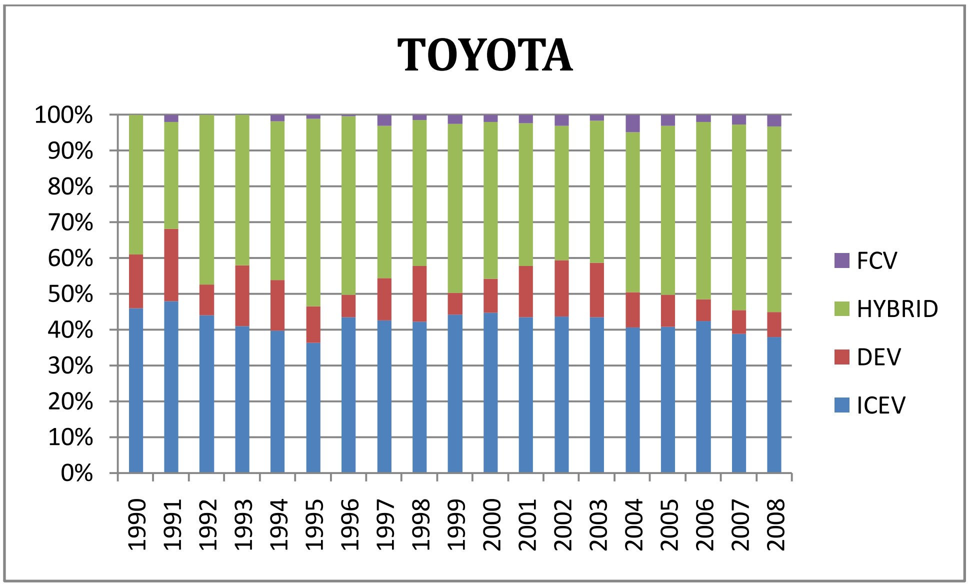
Finally, the patent portfolios per firm in Figure 4 indicate the persistent relevance of the Internal Combustion Engine as mode of propulsion. The part conventional engine technology (ICE and DE) has in the patenting activity as a whole is unmistakably large for almost all firms. Nonetheless, the larger firms in the sample slowly dedicate more effort in the development of mainly Hybrid solutions; which also span a larger part of the landscape – in particular in highly central activities – as they involve two types of propulsion. In essence, it combines the core technologies from ICEV and DE, with inclusion of activities in electrical engineering. Patent groups with a higher centrality in the Hybrid Vehicle sample as opposed to the general vehicle sample show that HV development focuses mainly on the control and arrangement of the electrical drive-train in a vehicle, but shares considerable overlap with earlier mentioned categories correlated to ICEV or DE development.

In contrast to HV technologies, which seem more complex and therefore span a wider part of the patent-landscape, FCV technologies are considerably more focused. It entails a set of patent groups that are closely connected to subclass H01M, which is defined as "methods for conversion of chemical into electrical energy." Moreover, it is located towards marginal parts of vehicle design as it is a distinct solution that may build less on existing technologies than other alternatives do, which could be indicative for the long way FCV has to go before it can be taken into production as an alternative.

Figure 4: Patent portfolios for all 15 firms 1990-2008



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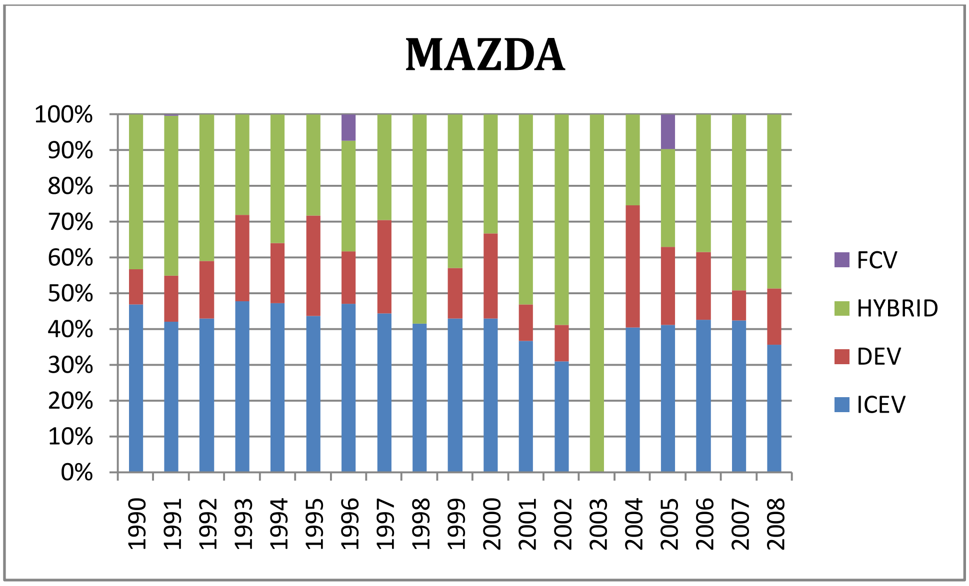
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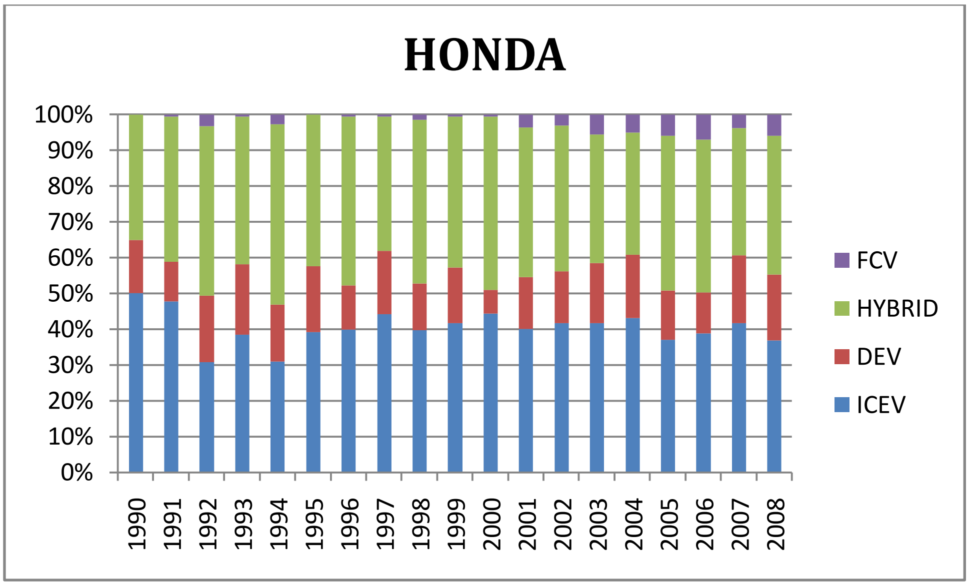
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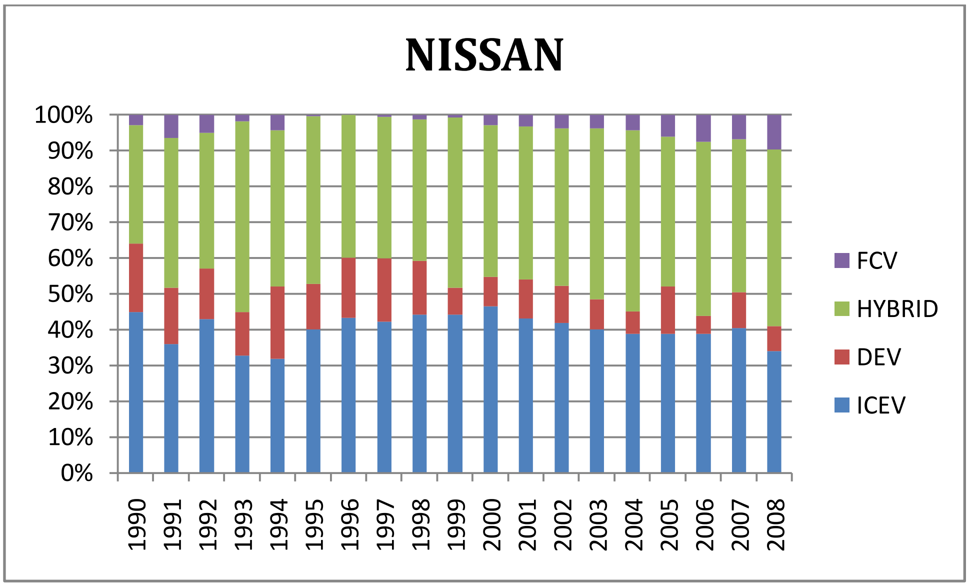
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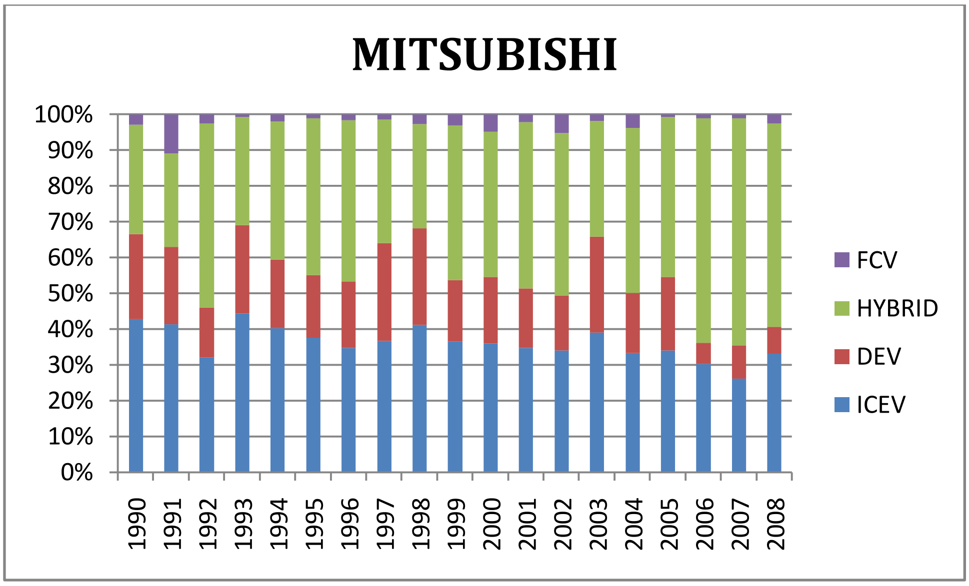
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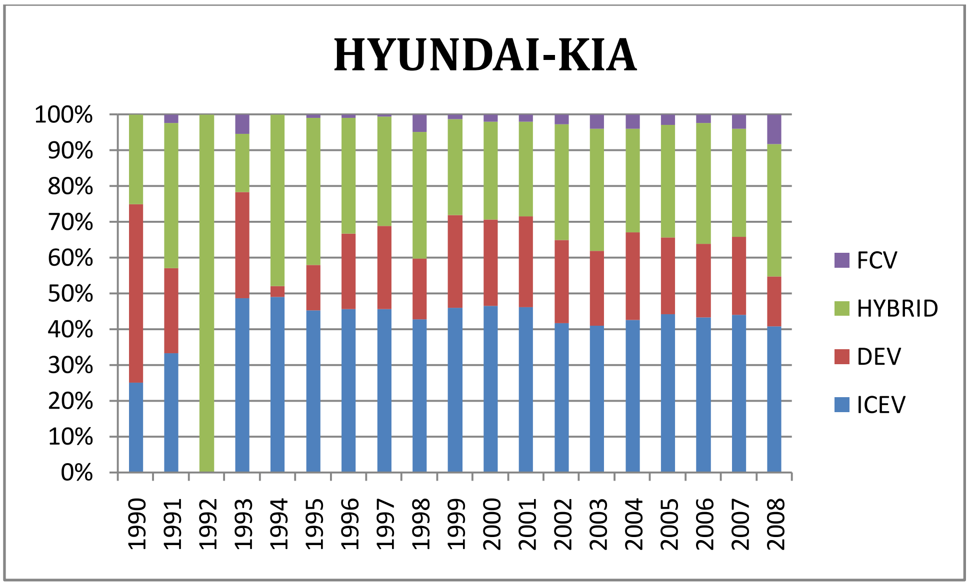
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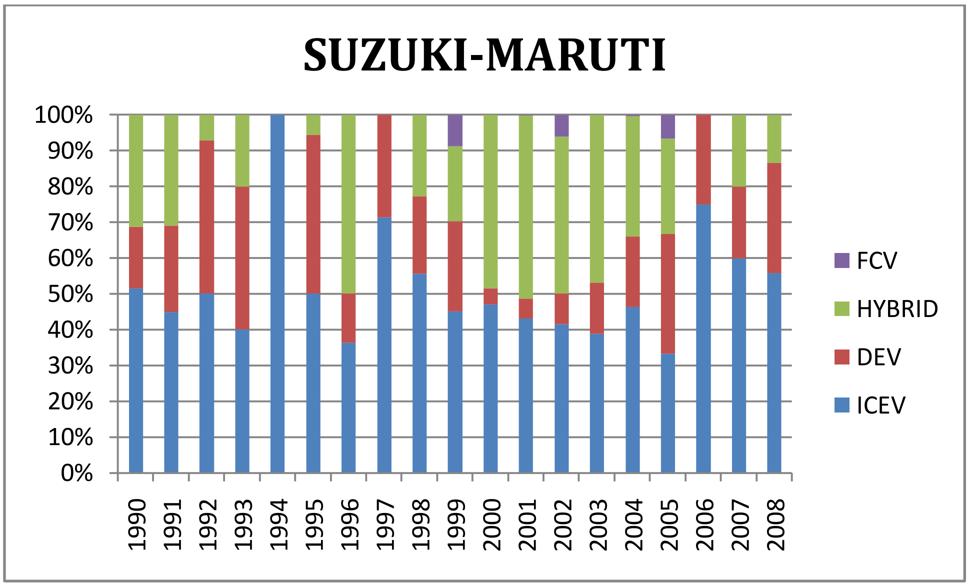
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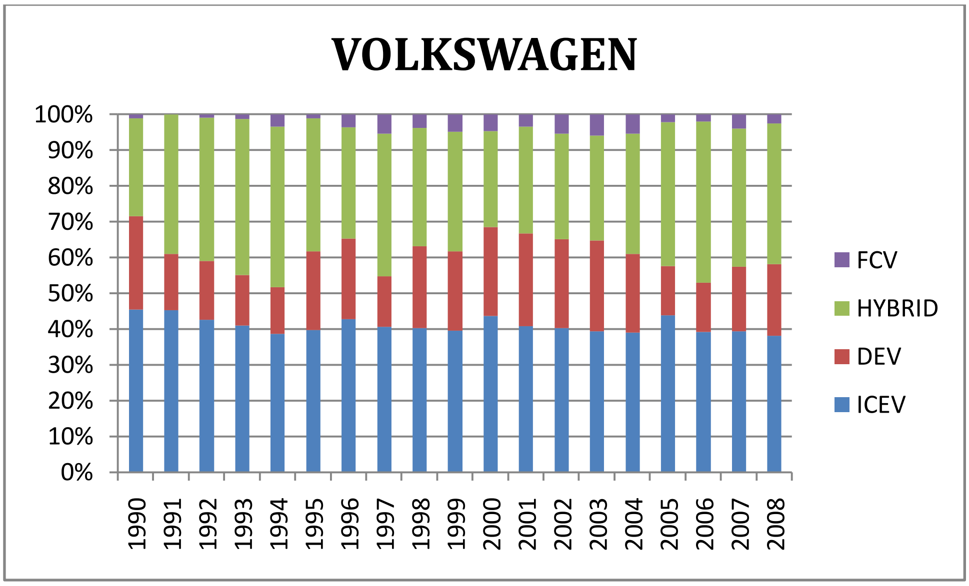
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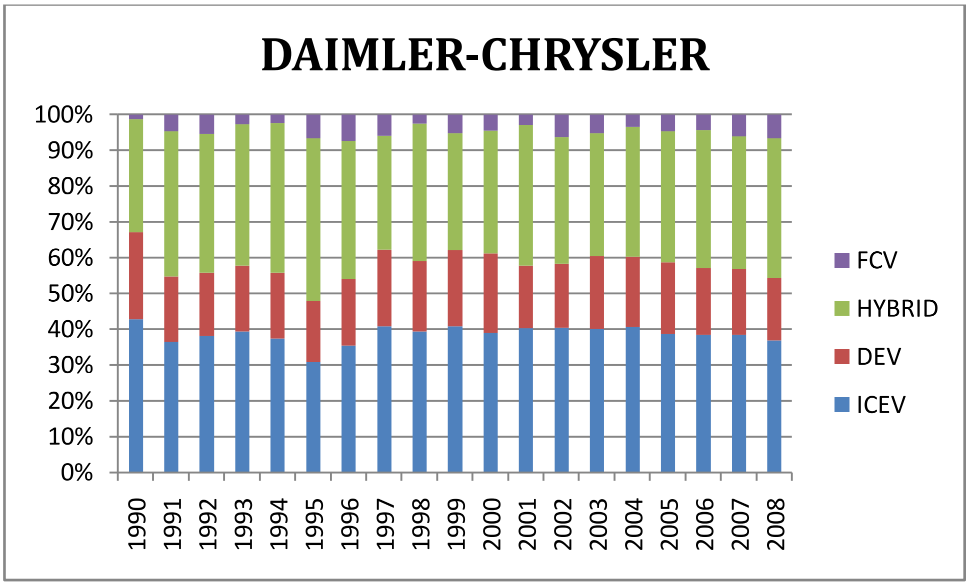
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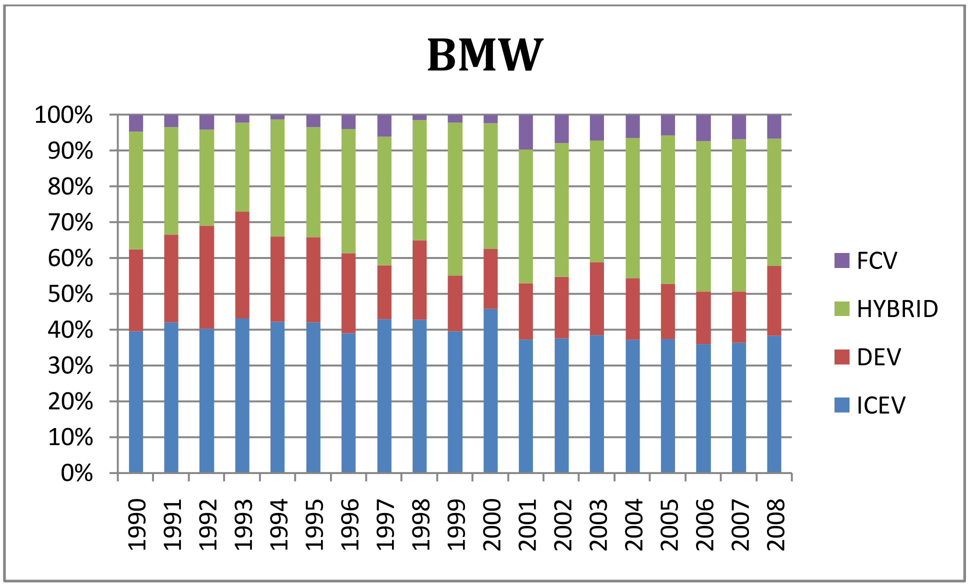
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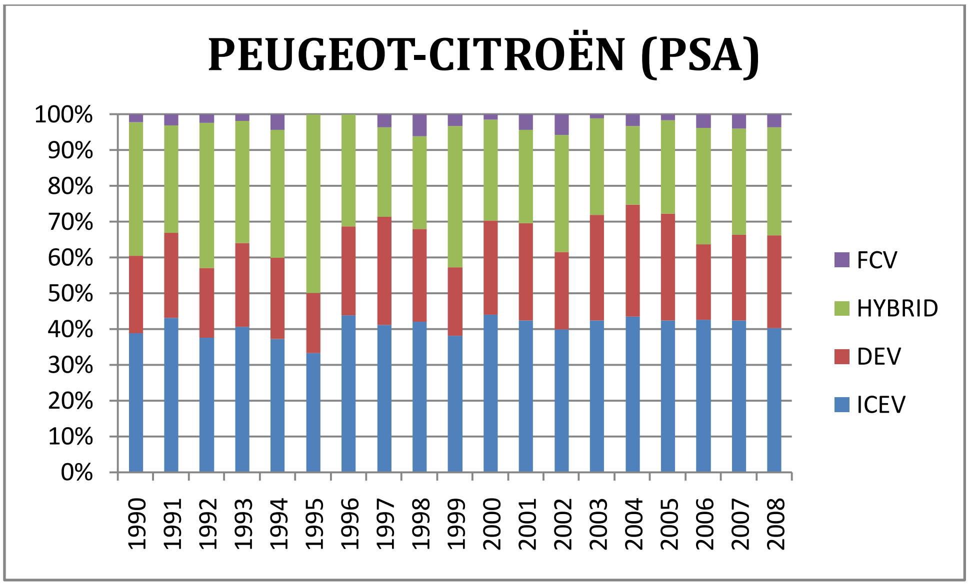
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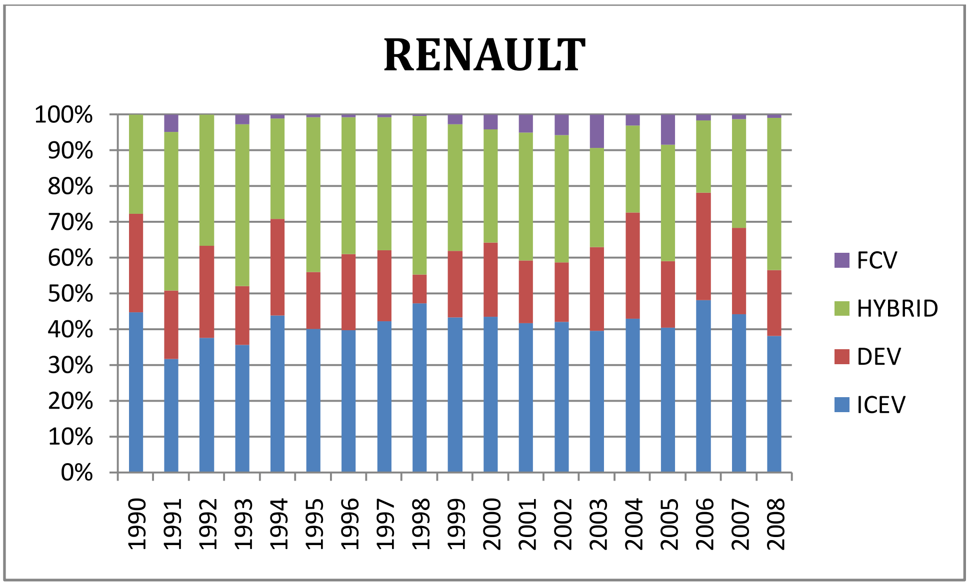
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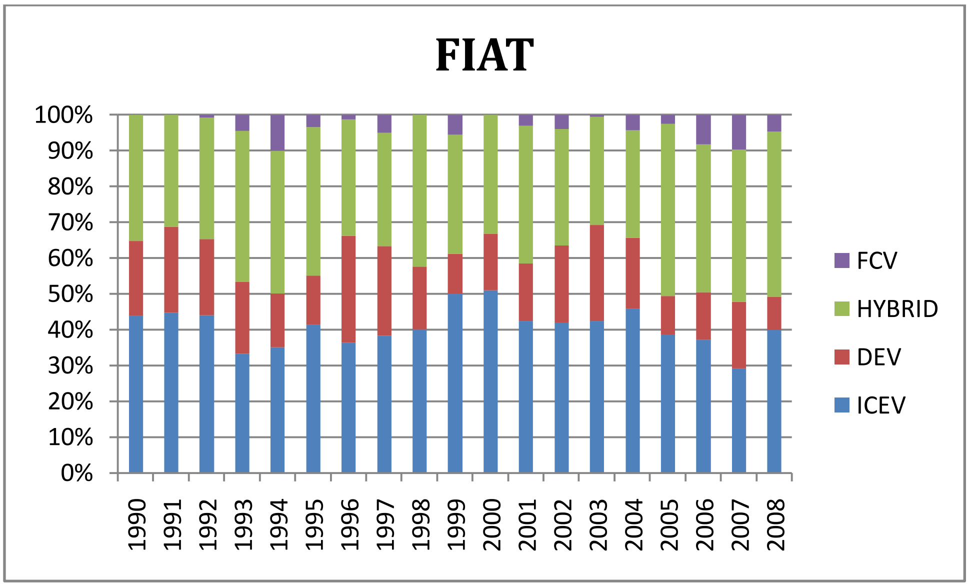

5. Conclusions

Discriminating technological activities is a daunting task, but is nevertheless an important issue for understanding innovation, sustainable development and technological trajectories. One particular source of problems finds its roots in the complex composition of technological solutions. Therefore, it seemed only logical to accept such complexity and put it to use by conceptualizing it in a relational framework. One important criterion to do so properly is trying to marginalize the ex-ante theorizing of sources or reasons of relatedness. Hence the problem is diverted to the trade-off between accounting for all possible entity-specific characteristics and asymmetries versus certain openness. Since this paper makes use of patent data, the latter option seemed more relevant.

The analysis of the patent data for this paper shows that there are several overlaps and some differences between the various environmental technologies. Even though combustion-based engines are the most mature technologies, they are not defined by the narrowest scope of patent groups. One possible reason is the continuous gradual improvement made in ICEV and DEV design, for which various alternatives are explored. Since the technology is well known, the dimensions of the technology in which beneficial gains can be made are more extensive. While FCV solutions are relatively new, solutions to existing problems are likely to be focused around key issues; the majority of manufacturers face similar problems in designing a workable technology. Hence, solutions to those early-development problems are likely to be reflected in a limited set of patents and patent groups. A good example concerns the Fuel-Cell Vehicle that faces clear challenges in improving its action-radius as well as the integration of the drive-train. Solutions offered focus on a fixed range of opportunities and activities and it is therefore not surprising that the scope of patent groups is relatively narrow. Yet as FCV innovations take place on the fringes of the patent-landscape, it remains to be seen to what extent they will actually be implemented in vehicle design.

The observed hybridization of LEV design (Frenken, Hekkert, & Godfroij, 2004; Oltra & Saint-Jean, 2009) can partly be corroborated by the results presented in this paper, since hybrid solutions can be distinguished in the more central part of the patent-landscape. Hybrid technologies built on knowledge about combustion engines as well as electrical engineering. This extensive scope of skills logically increases the susceptibility to beneficial knowledge spill-overs. However, such reasoning would only be justifiable on the premise that both engineering skills would be central and related, which is in fact the case. More importantly, if a process of hybridization has been concluded some years ago, it may have given rise to the electrification of vehicle propulsion as suggested by the results presented in this paper. Activities in electrically oriented categories related to ICEV design may have induced incentives for hybrid technologies to be investigated and subsequently may also have stimulated the exploration of related activities that can lead to purely electrically propelled vehicles. Hybrid Vehicle technologies share the advantageous location in the central part of the patent landscape. However, hybrid technology shows to be mostly compatible with both existing and alternative solutions.

The fact that the leading HV on the European and US market has been introduced by Toyota is, considering the overlap between technologies and manufacturer's activities, not fully explained by the results presented in this paper. However, Europe's largest manufacturers seem not to be very active in patenting technologies related to electric propulsion. Neither is Ford or GM. However, it is a very important node in the development of hybrid and possibly electrical solutions. Even though European firms may display the most diverse patenting behaviour in classes that matter for vehicle development as a whole, further analysis indicated that there may be more niche-related technological activities of strategic importance. Missing the in-house capacity to produce such technologies may result in a competitive disadvantage in the future. Supposedly, the typical Japanese Toyota-business model of large industrial conglomerates producing a variety of related products without losing focus may be the essential difference. For that matter, the vertical disintegration of mainly European companies may induce innovative behaviour among suppliers that eventually spill over, but it can have an important drawback in terms of losing in-house related variety and therefore missing the capacity to innovate and create competitive advantages over time. Specifically since the competition between old versus new is uneven – FCV technologies for instance are seem not to be part of the core-competences of the manufacturers investigated here – intermediate solutions like hybrid technologies become ever more relevant. Perhaps, if key problems are resolved in the near future, Fuel Cell technology may become a more serious candidate but the competitive advantage shifts from technological characteristics to infrastructure advantages. So far, it seems that hybrid vehicles are the most logical alternative in the near future and they are likely to be produced by Japanese firms.

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