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Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis

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La diversité des trajectoires technologiques dans les véhicules à faible émission : une analyse à partir de données de brevet

Résumé

L'article a pour objet d'étudier la diversité des technologies de moteur pour les véhicules à faible émission qui sont développées par les constructeurs automobiles dans le but de remplacer les modèles traditionnels basés sur la combustion interne. L'objectif est d'analyser la compétition entre les différentes technologies destinées aux véhicules à faible émission ainsi que les stratégies d'innovation des constructeurs automobiles. Nous proposons d'abord une définition et une représentation des trajectoires technologiques afin de comparer leurs performances et d'identifier leurs forces et leurs faiblesses. Les obstacles technologiques, les freins à l'adoption de ces moteurs alternatifs ainsi que les caractéristiques de la compétition technologique en jeu sont ainsi mis en évidence. Nous utilisons ensuite des données de brevets pour étudier les portefeuilles de brevets des principaux constructeurs automobiles dans ces technologies sur la période 1990-2005. L'analyse met en évidence la diversification progressive des portefeuilles de brevets des firmes sur l'ensemble des technologies de moteur ainsi que le positionnement stratégique différencié des constructeurs automobiles selon le pays d'origine.

Mots-clé : véhicules à faible émission ; innovation environnementale ; compétition technologique ; brevets.

Variety of technological trajectories in low emission vehicles (LEVs):
a patent data analysis

Abstract

This paper focuses on the diversity of engine technologies for Low Emission Vehicles (LEVs) that are developed by car manufacturers in order to substitute for the conventional internal combustion engine vehicle. Our purpose is to analyse the competition between the various technologies for LEVs as well as the innovative strategy of car manufacturers. We first propose to define and to represent these technological trajectories in order to compare their performances and to identify their strength and weaknesses. The technological bottlenecks, the barriers to the adoption of these alternative engine technologies as well as the features of this technological competition are underlined. We then use a patent data analysis to study the patent portfolios of the main car manufacturers in these technologies on the period from 1990 to 2005. The dynamics of patents applied by car manufacturers gives insight on the competition among technologies and on the strategy of firms. This analysis emphasises the progressive diversification of firms patent portfolios over the whole set of engine technologies and the differentiated strategic positioning of car manufacturers according to countries.

Keywords: Low emission vehicles; environmental innovation; technological competition; patent data

JEL: O33; Q55; L62

Introduction

Under the pressure of regulation, the automotive industry has to cope with environmental concerns, in particular with the reduction of polluting emissions (CO₂, NO_x, particles), of fuel consumption and noise, as well as with the recycling of end of life vehicles. This regulatory context has encouraged R&D and innovative activities of car manufacturers and suppliers. The Zero Emission Vehicle Mandate introduced by the Californian Air Resources Board in 1990 gave an important impulse for the development of low emission vehicles (LEVs). This technology-forcing regulation primarily focused on electric vehicles. But electric vehicles did not lead to a sizeable market and its commercialisation failed due to the unsatisfying performance characteristics of battery technology. That is the reason why other technologies started to be supported such as fuel cells vehicles and hybrid vehicles. This evolution leads to a technological competition between the different technologies for LEVs.

In this paper, we focus on the diversity of engine technologies for LEVs that are developed by car manufacturers in order to substitute for the conventional internal combustion engine vehicle. Our purpose is to analyse the competition between the various technologies for LEVs as well as the innovative strategy of car manufacturers. In the first section, we propose to define and to represent these technological trajectories in order to compare their performances and to identify their strength and weaknesses. We discuss the technological bottlenecks, the barriers to the adoption of these alternative engine technologies as well as the features of this technological competition. In section 2, we use a patent data analysis to study the patent portfolios of the main car manufacturers in these technologies on the period from 1990 to 2005. The dynamics of patents applied by car manufacturers gives insight on the competition among technologies and on the strategy of firms. This analysis emphasises the progressive diversification of firms patent portfolios over the whole set of engine technologies and the differentiated strategic positioning of car manufacturers according to countries.

I. Technological variety and competition in LEVs

1.1. The different competing technologies for LEVs

Under the pressure of environmental regulation, in particular the Zero Emission Vehicle Mandate introduced by the Californian Air Resources Board in 1990, car manufacturers try to develop more efficient engine technologies. The aim is to develop low emission vehicles (LEVs) which are able, in the medium and long term, to comply with environmental standards. The main environmental concerns are CO₂ and NO_x emissions, fuel consumption, energy efficiency and engine noise. These environmental concerns have created new technological opportunities in the field of motor vehicles and engines, which lead to an intense activity of environmental innovations. As a result different engine technologies are explored and developed in parallel by car manufacturers. Our purpose is to analyse how these various technologies compete and how car manufacturers try to combine the different technological options. We first present and discuss these various engine technologies.

- Internal combustion engine vehicles (ICEVs)

The car industry is characterised by a strong and persistent dominant design which is the internal combustion engine vehicle (ICEV). Since ICEV is already a very mature technology,

it is unclear whether this technology is able to meet future environmental regulations and emission standards. Nevertheless during last decades, ICEVs have been significantly improved by innovations like direct injection technologies, the *Common Rail* technology, *Stop and Go* systems, particle filters and new materials to lighten the vehicles and to decrease frictions. So a cluster of innovations has been developed which has enabled to decrease fuel consumption, polluting emissions and noise rate, and to increase energy efficiency of engines. This is particularly true for diesel engine vehicles which environmental performances have strongly been improved.

In Europe diesel vehicles represent an important share of the market: the share of diesel cars in first registration of passenger cars in 2002 is 63% in France, 57% in Spain, 43% in Italy, 23.5% in UK, 15% in Finland and 0.7% in Sweden (European Commission, 2004). These figures also reveal the differences among countries resulting from different technological choices. In contrast diesel cars are less present in the American market because the incentive to buy is much weaker (due to a smaller price premium for diesel in comparison with gasoline) and due to the fact that diesel cars have difficulties to meet the environmental standards. The European and Japanese car manufacturers are leading in the production of diesel technologies and related innovations¹. Resistance in the US and in Japan has been motivated by the potentially carcinogen properties of microscopic soot particles in diesel exhaust gases, by their high noise levels and comparatively poor acceleration, although recent innovations have largely addressed both these issues (Maxton and Wormald, 2004).

Now diesel cars are far more powerful, refined and quiet, and so offer a particularly attractive solution for reducing fuel consumption and carbon dioxide emissions. The future development of diesel cars will depend on fuel availability and fuel price, but also on their environmental performances. As a consequence, we can even find signs of a revival of interest in the US for diesel engines which leads to forecast an increase in diesel penetration in the future ten years (Maxton and Wormald, 2004). In Europe the strategic research agenda also emphasizes that "In the time period to 2020, the main improvements in energy use and GHG emissions will come from efficient ICE and their associated advanced fuels" (ERTRAC, 2004, page 42). The main research topics planned in this agenda are advanced ICE (high specific torque, advanced fuel injection, flexible components...), new combustion concepts (controlled auto-ignition, extended homogeneous range in diesel engines, integrated combustion process...), fuels and lubricants for advanced ICEs, improved design elements and biomass derived fuels. Thus the dominant design of ICEV is still under progress even if the technology is considered to be mature. In terms of environmental performances, this technology competes with three alternative engine technologies that are electric vehicles, fuel cell vehicles and hybrid vehicles.

- Electric vehicles (EVs)

In the beginning the Californian ZEV mandate created a window of opportunity for EVs but did not lead to a sizeable market for such vehicles (Kemp, 2005). The advantages of electric engines compared to conventional ones is that they do not emit any emissions during use, are quiet and have less moving parts which reduces the need for maintenance. But the main disadvantage is that the energy supply required to power the vehicle needs to be stored as electricity on board. The batteries that are needed are expensive, have a short lifecycle and have a limited storage capacity. The range of use of these vehicles is therefore much smaller

¹ Japanese manufacturers produce diesel cars mainly for the European market and the 'third world' market.

than other conventional ones, and in particular they are not adapted to intensive use. A large amount of research has been done on alternative systems of battery but with no sign of a breakthrough. Their much greater cost is not sufficiently compensated for by gains in power density, battery life or speed of recharging. That is the reason why EVs are not considered to be a competitive alternative to ICEV anymore. Consequently the regulatory requirements have been adapted and the window of opportunity has changed to hybrid and fuel cell vehicles. Nowadays EVs are limited to niche markets dedicated to specific uses such as delivery vehicles, airport shuttles and urban buses. Thus EVs first considered at the beginning of the 90s as an alternative to conventional vehicles, which can be mandated by law with the ZEV mandate, became an alternative technology restricted to certain niches of the market. R&D activities and patents of automotive firms confirm this evolution since we can observe a rise and fall of EVs patents between 1990 and 2002 with a top in 1996 (Van den Hoed and Vergragt, 2003). The EV is currently not considered by the automotive industry anymore, which reflects an *ex post* selection process, and there is a shift in research focus from EVs to both hybrid and fuel cell vehicles.

- Fuel cell vehicles (FCVs)

A FCV is defined as a vehicle driven by an electric engine which is powered by a fuel cell. A fuel cell is an electrochemical cell which can convert the chemical energy of a fuel such as hydrogen into electrical energy. There are different basic types of fuel cell distinguished by their different electrolytes. In terms of environmental performances, when the fuel is hydrogen the system does not generate any pollutants. The only emissions are unused oxygen, nitrogen and water, which may be present in either liquid or vapour form. FCVs also have the same advantages as a typical electric engine that is the possibility to regenerate 'breaking energy', the omission of transmission and the low noise rate.

The major problem with this technology is the fuelling of vehicles. Hydrogen can be fuelled directly in the vehicle or be produced on board when other fuels like gasoline or methanol are used as fuel. In the last case, fuel conversion leads to unwelcome emissions, involves a complicated technical process and reduces the energy efficiency of the system. Moreover when FCVs use a fuel converter, the global level of emissions if we account for all the steps from "well-to-wheels" is not significantly lower for hydrogen vehicles than for ICEVs.

A conventional engine simply needs a tank of gasoline or diesel fuel. A FC engine needs a supply of very pure gaseous hydrogen (impurities inactivate the cell). Fuelling infrastructure, costs, reliability and durability are the critical hurdles that FCVs have to overcome before they can achieve their development. The fact that the FC technology needs a new fuel distribution and retailing infrastructure involves huge costs² and is a big problem for the passenger car fleet which is very widely dispersed. Furthermore this infrastructure would have to operate in parallel with the conventional fuel distribution network, as it would take decades for the huge fleet of vehicles to switch over completely.

Another issue pointed out by Maxton and Wormald (2004) is that the great majority of the subsystems and components being developed for fuel cells are based on technologies that are almost wholly alien to the car industry. This will create substantial challenges and the

² The cost of a full hydrogen distribution network for the US has been estimated at \$100 billion (Maxton and Wormald, 2004).

need for carmakers to build up new supplier bases. This will strongly affect the relationship between car manufacturers and their suppliers³.

All this does not make the widespread deployment of FCVs a wildly attractive proposition, either financially or environmentally speaking. That is the reason why the research activities on FCVs result in prototypes for limited range of use, such as urban transit buses and taxis. As a consequence, it seems that FCVs will remain restricted to captive niche markets for governmental agencies or some specific enterprises.

- Hybrid vehicles (HVs)

The application of hybrid technology looks promising. Given present limitations in technologies such as batteries and fuel cells, the most viable powertrain alternatives are hybrid configurations that include a relatively small internal combustion engine and an electric motor. A HV system seeks to operate a conventional engine at maximum efficiency or turn it off. It then provides propulsion through an alternative source. This is more efficient in terms of fuel use and less polluting in terms of emissions. The HV can be equipped with either a gasoline fuelled ICE as well as a diesel engine, the latter being more efficient. HVs can have serial or parallel propulsion systems depending on the way the combustion engine, the electric engine and the batteries are connected. These vehicles can be fuelled with conventional or alternative fuels. Compared to a serial system, the parallel system can deliver more power due to the simultaneous use of combustion engine and electric engine.

This technology is generally considered to be a transition technology between current internal combustion engine vehicles and fuel cell vehicles. One of the advantages of this technology is that it is competitive, in comparison with the internal combustion engine, in terms of range of use and speed, with a total efficiency which can be twice as high as the efficiency of the combustion engine (Frenken and al. 2004). Previously positioned as an intermediary solution towards new technologies, the HV has always played a modest role in sustainable mobility. Nevertheless its recent commercial success and its environmental performances slowly change the perspectives for this technology: instead of being developed side by side HVs might in fact form a competitive threat to the commercial development of FCVs (Hekkert and van den Hoed, 2004). The main advantage of HVs is that they are compatible both with the available fuel infrastructure as well as with the current ICE system. In terms of emissions, HVs score very well, especially when diesel is used as fuel, and a good energy efficiency is realized by harnessing the kinetic energy generated when the car brakes.

HVs cover a multitude of possible propulsion architectures, from a pure battery electric with a small ICE powered generator on board to extend its range, to a pure ICE driveline with a bit of additional power and regenerative braking capacity via a special starter alternator. The former is called EV ER (electric vehicle, extended range). Work at the University of California has shown that such vehicles can achieve very low levels of fuel consumption and low levels of emissions (Maxton and Wormald, 2004). The latter are called electric boost vehicles which approximately use 10% of electricity as an energy source. So HVs correspond to a range of technological options resulting from the hybridisation of a conventional ICE and an electric propulsion system. Each option can be characterized by the share of electricity used as an energy source. For example, the Toyota Prius is around 30% of electric power

³ The fact that the company that has done the most to develop proton exchange fuel cell based on road vehicle propulsion systems, Ballard, is owned by Daimler Chrysler and Ford is an additional challenge to their competitors (Maxton and Wormald, 2004, page 82).

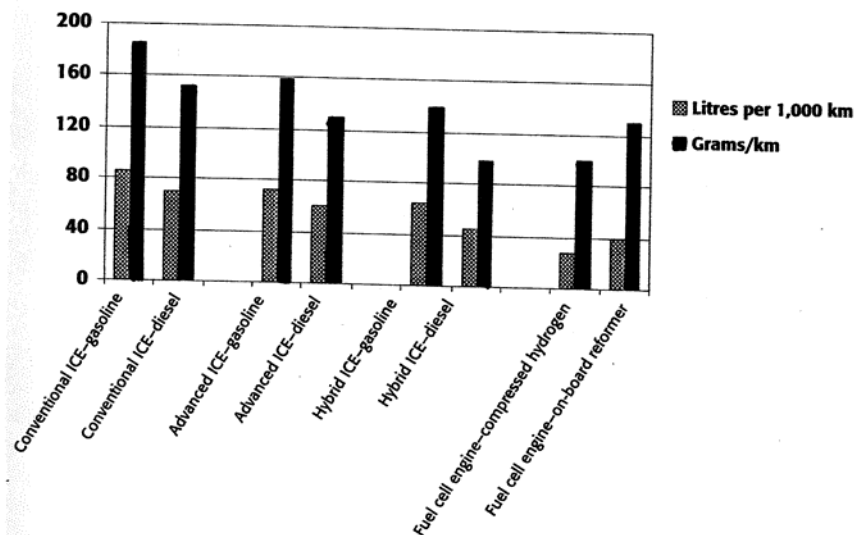
capacity (Maxton and Wormald, 2004). Thus HVs also have the advantage of offering a large range of hybrid configurations and so of use.

1.2. Environmental performances and range of use of LEVs

In order to be efficient and to further develop, each engine technology has to combine several dimensions in terms of environmental performances, engine efficiency, price and range of use of the vehicle. The ability to combine these dimensions is essential to the development and the diffusion of LEVs. This point is critical for the development of clean technology in general (Oltra and Saint Jean, 2005). This argument is even stronger in the case of the automotive industry which produces a complex system product that requires firms to coordinate a broad array of different sources of knowledge and technology. Each LEV technology presents some advantages in terms of environmental performances and/or performances of the vehicle (efficiency, price and range of use), but no technology is better on all the criteria. In other words, there is no one best technology.

In terms of environmental performances, in particular carbon dioxide emissions, figure 1 shows that the hydrogen fuelled FCV and the diesel-hybrid vehicle show the largest potential compared to conventional ICEVs. But the performances of FCVs fall down as soon as one puts an on-board reformer. We also see that for fuel consumption the best potential for reduction is obviously FCVs. This figure also shows that advanced diesel vehicles exhibit very good performances. Finally the best combination between fuel consumption and carbon dioxide emissions is obtained by diesel-hybrid vehicles.

Figure 1: Fuel consumption and CO₂ emissions for the different engine technologies

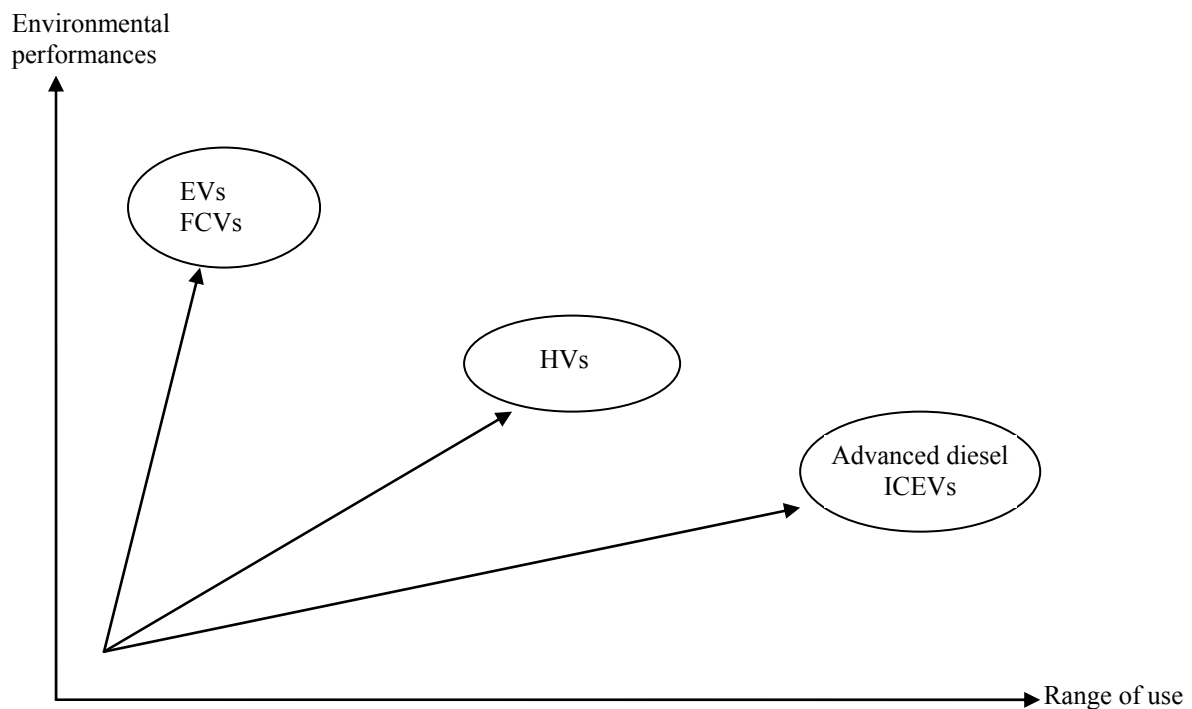


Source: Maxton and Wormald, 2005, page 85

Nevertheless the development and the diffusion of engine technology strongly depend on the price of the technology and the range of use of the vehicle. In particular the range of use is a critical point for LEVs. EVs and FCVs are less suitable for intensive use which restricts their development to niche markets. HVs present more flexibility due to the combination of ICEV and electric engines, but they remain more adapted to light vehicles. So it clearly appears that the ability to combine environmental performances with the range of use is a key determinant of the development of LEVs.

As represented in figure 2, the development of LEVs can be summarised by three technological trajectories characterised by their ability to combine these two dimensions. HVs correspond to what we called in Oltra and Saint Jean (2005) a "median strategy" which is often the most efficient since it associates the environmental performances with the performances of the product. The performances of the product are often critical in the development of clean technologies since they often entail a destroying competence effect that alters certain characteristics of the product (Oltra and Saint Jean, 2005). In the case of the automotive industry, the characteristics that are critically modified by the change in engine technology are the power efficiency of the vehicles and the types of fuel (the problem of fuel infrastructure is tackled in the next section).

Figure 2: Technological trajectories for the development of LEVs



The resulting range of use of LEVs determines their potential market. The example of the EV illustrates this argument since, in spite of its promising environmental performances, its development has been completely blocked by the very low performances of the vehicle in terms of autonomy and power efficiency. On the contrary HVs show considerable market success, especially the Toyota Prius which sales have considerably increased since 1998 in North America and in Japan. The Toyota Prius II really exhibits a good compromise between

power engine, fuel consumption, carbon dioxide emissions, noise rate and drivability of the vehicle, which will certainly boost its sales. We can say that for now this hybrid technology is the most promising because of its ability to combine environmental performances with the performances of the vehicle.

But even if the HV is a solid competitor to the ICEV, the conventional engine is by no means played out. The diesel ICEV is still under improvement and has significantly increased its environmental performances through innovations such as direct injection and particle filters. European car manufacturers bet on this technology for the future (in particular Peugeot) since they argue that they will be able with the advanced diesel to exhibit the same performances than HVs in terms of carbon dioxide emissions and fuel consumption for a very lower price.

1.3. Technological competition between ICEV and LEVs and among LEVs

The development of LEVS corresponds to a typical case of technological competition between an established technology, or a dominant design, and a set of alternative technologies. Evolutionary economics emphasises that in that case market selection may select a suboptimal technology as increasing return to adoption renders the process of technology selection path dependent (Arthur, 1989, David, 1985). Path dependency can create lock-in on suboptimal technology because self-reinforcement effects stabilise one technology and inhibit the transition towards a new one. Arthur (1988) identifies five sources of path dependency which are learning by using, network externalities, scale economies in production, informational increasing returns and technological interrelatedness. As a consequence even if a superior technology is introduced in the market, technological substitution is not warranted because the established technology benefits from increasing returns to adoption. And when technological substitution does take place and several new technologies are competing, market selection can select a suboptimal technology due to path dependence of sequential adoption decisions.

In the analysis of technological competition, it is often assumed that the competing technologies meet similar functions. This statement is not a trivial one because of the huge amount of features that usually characterise a technology. Whenever a new technology fails to be successful, we therefore have to analyse carefully whether it did so because it was impeded by the dominance of the established technology or because it was simply inferior with regard to the functions it was supposed to fulfil (Sartorius and Zundel, 2005). In other words, technologies often do not serve as perfect substitutes. This notion of functions of technology is helpful to distinguish two kinds of technological competition. In many cases, the solution of an environmental problem defines a new function and several technologies executing this function compete on the level of what Sartorius and Zundel (2005) call *new-versus-new* competition. In order to be accepted by consumers, the new environmentally improved technologies also have to fulfil the genuine function of the established technology they are supposed to replace. This gives rise to an *old-versus-new* competition. In our case, this last type of competition concerns the competition between ICEVs and LEVs, while the *new-versus-new* competition occurs between EVs, FCVs and HVs. Both types of competition need to be analysed in close relation since there are mutual interactions between them.

The old-versus-new competition between the ICEV and LEVs can be studied as a problem of competition between a strong dominant design and a set of alternative new technologies. The barriers to the development of new technologies are mainly linked to

economies of scale and scope, as well as to learning effects and network externalities. The dependence of the ICEV on a network of filling stations is a source of network externalities. The degree of compatibility of the new engine technologies with the existing network and infrastructure is a crucial factor of this old-versus-new competition. Indeed a significant change of the fuel infrastructure involves huge costs which create strong barriers to the adoption of a radically new engine technology. This is particularly the case for FCVs fuelled with hydrogen. This can lead to strategic behaviours in order to keep the current fuel infrastructure and so to create compatibility between the established technology and the new ones. An example is the development of a fuel reformer by Shell to convert gasoline in hydrogen on board of the vehicle (Hekkert and Van den Hoed, 2004). The barriers to the implementation of new engine technologies for LEVs are also linked to the accumulation of knowledge and competencies on the established ICEV technology which creates strong irreversibilities. These irreversibilities are reinforced by the vertical relationships between car manufacturers and their suppliers which can be affected by new engine technologies. In other words, the more radical and the more global the innovation, in the sense that it requires many changes in the linkages between actors, the stronger the implementation barriers (Hekkert and Van den Hoed, 2004). These features tend to favour the persistence of the ICEV dominant design and to spur incremental innovations on this design⁴.

The new-versus-new competition between EV, FCV and HV is governed by the same forces as the old-versus-new competition. The main difference consists in the point of departure of the competition, since in the former case the initial competitive advantage is fundamentally in favour of the established technology. The new alternative technologies have to build up progressively their competitive advantage. In the case of LEVS, this new-versus-new competition is really important since various technological options are explored. This exploration of alternative engine technologies leads to a race to innovation and to specific strategic positioning of car manufacturers. The competition between EV, FCV and HC is characterised by an evolution in the priority of research activities and in the strategy of car manufacturers. From 1990 to 1996, the EV was considered to be a serious alternative to ICEV. Given the constraints on the batteries and the range of use of the EV, there was a change in perspectives and the FCV appeared progressively as the most promising technology. Since 1997-1998 the vast majority of the automotive industry has embraced the fuel cell leading to large research and development activities (Hekkert and Van den Hoed, 2004). Previously positioned as an intermediary solution towards radically new technology such as FCV, the HV developed progressively and plays now a dominant role. The main advantage of the HV is its compatibility with the ICEV dominant design and with the available infrastructure, while the FCV requires changes at both levels. As a result the HV will experience much less barriers than the FCV. This competitive advantage of the HV is linked to the fact that the hybridisation of technologies enables to exploit technological complementarities between the internal combustion engine and the electric one.

Technological complementarities play an increasing role in this competition among LEV technologies since spillovers exist between technologies. For example, the improvements of EVs have benefited to HVs, as well as the innovations on HVs benefited to the FCV. Moreover we also observe that research activities on fuel cells result in the development of the use of fuel cells for the feeding of electronic and electric devices of ICEVs. As a matter of fact, there is an increasing overlapping of technologies which enables

⁴ Anyway the persistence of ICEV for a rather long time is unavoidable since it will take a very long time to replace the whole car fleet.

car manufacturers to exploit technological complementarities between alternatives, to progress step by step and to improve continuously the ICEV dominant design. This overlapping of technologies is a way of building a gradual path towards radically new engine technologies. As a result the technological competition among LEVs is characterised by a persistent diversity of options, no signs of premature lock-in⁵ and increasing complementarities between technologies which mainly benefit to the HV.

II. An analysis of patent portfolios of car manufacturers

II.1. Method and data

Data on patent applications from 1990 to 2005 come from the Europe's network of patent databases (esp@cenet Portal⁶) based on the European Patent Office. (EPO). We used the Worldwide database since it covers published patent applications from more than 70 countries and regions and is the most comprehensive collection of documents in espacenet.

We selected eleven car manufacturers according to the top sales ranking in output units in 2002 (European Commission, 2004). The sample of firms under study thus comprises Toyota, Honda, Renault, Ford, Nissan, Mitsubishi, Hyundai, General Motors, PSA, Daimler-Chrysler and Volkswagen. This selected sample is also justified by our purpose to compare the strategies of American, Japanese and European, in particular French and German, car manufacturers. Indeed these three regions tend to prefer different designs based on national driving conditions and the regulatory context. The dynamics of patents applied by the main car manufacturers can thus give insight on the competition among technologies for LEVs and the strategy of firms.

In order to apprehend the various technological trajectories examined in the first section (ICEVs, EVs, HVs, FCVs), keywords were identified and used to extract the corresponding patent applications and then to count the number of patents applied by each car manufacturer on each technology. Different keywords were selected: internal combustion engine vehicle (ICEV), diesel engine (DE), fuel cell vehicle (FCV), electric battery vehicle (EBV) and hybrid vehicle (HV). This enables us to examine the cumulated number of patents in each technology per firm as indicative of a firm-specific accumulation of knowledge and advancement of technological trajectory⁷. Concerning the dominant design two expressions were used, ICEV and DE, in order to isolate the innovations dedicated to diesel vehicles. Indeed as discussed in section 1, there is a strong debate on the future of advanced diesel vehicles which, according to certain car manufacturers, will be as efficient as hybrid vehicles.

So in order to perform the search, three search fields were combined: 'keywords in title or abstract', 'publication date' and 'applicant'. As expected, keywords are words which can be found in the title and/or abstract of the patent document. The publication date is the date on which a patent application was published for the first time. The applicant is the person or organisation (companies, universities) who filed the patent application.

The keywords method offers a simple way to extract a set of potentially relevant patent applications. However several drawbacks have to be underscored regarding this keywords

⁵ Frenken and al. (2004) show through a patent data analysis that premature lock-in is unlikely to occur.

⁶ <http://ep.espacenet.com>

⁷ Moreover cumulative distributions of patents can underscore the effects of increasing returns in R&D activity (Frenken et al., 2004).

method. First, the combination of words though linked by the operator AND does not guarantee from finding a patent document that matches the exact query. Indeed typing the keywords in the title or abstract search field enables to find patents having the specified words in the descriptive part even if they are not connected to each other. So the search includes documents in which the invention is described with the various different terms but has nothing to do with what is searched for. This was particularly true for the item 'electric vehicle'. As a consequence of that, the number of EV patents proves to be excessively high since it incorporates not only inventions for EV *stricto sensu* but also inventions combining electric and electronic devices embarked in a vehicle. Although it is symptomatic from the growing penetration of electric and electronic devices in the car system (Lung, 2004), this creates a bias in the relevant patent set. This is the reason why we chose to narrow down the search for EVs by considering in addition the word 'battery' in the title or abstract search field. It resulted in specifying better the sample of relevant patents. Likewise for the item 'hybrid vehicle' it is hard to separate the inventions that do concern hybrid cars from those that concern a car solely powered by a combustion engine but including the hybrid term in its description.

Related to this drawback, the keywords method makes it difficult to separate different types of innovation. For example, hybrid cars are able to make use of the electricity produced on board for additional functions which gives it a decisive advantage compared to combustion engine cars. Advances relative to the use of electricity produced on board are different from progress made on the only drive mechanisms of hybrid systems. But the keywords method does not enable to distinguish between these two types of invention. One can also imagine fuel cells applied for supplying individual electronic equipment incorporated in a vehicle and not for powering automobiles. Again the keywords method could not easily separate both inventions. In order to control this problem as far as possible, relevant patents should then be screened by reading abstracts of screened patents.

A last drawback is linked to the duplication of patents that are subject to application in different countries. So one and the same patent can be counted three times if it has been applied in Japan, in US and in Europe. In spite of this bias, duplicate patents were not eliminated from the sample in this version of the paper. As a consequence an innovation which is patented world-wide is counted several times and so is overweighted in our data set. Nevertheless the fact that an innovation is patented world-wide is also a signal on its strategic dimension which can justify an overweighting of this innovation.

More generally, using patenting activities as an indicator of innovation is not without raising problems. First, not all inventions or innovations are patented. So patents give only a partial representation of innovation activities. Second, the patenting activity tends to vary according to the sector and to the point in time under investigation. So depending on the sectors, firms may prefer other appropriation modes and may protect innovations by trade secrets and copyrights instead of patenting. Lastly national differences exist between patent systems in terms of demanded degree of novelty and constraints attached to the patent system in its whole. For example it is less expensive to patent in Japan than in the US or Europe such that it results in an overrepresentation of Japanese patents⁸.

⁸ Moreover the differences among countries in terms of the required degree of novelty, the flexibility of legislation and the first-to-file or first-to-invent systems also influence the propensity to patent.

However patent data are a 'unique resource for the analysis of the process of technical change', providing an abundant quantity of available information with potential industrial, organisational and technical details (Griliches, 1990). Moreover we argue that patenting is part of the technological responses from some industries, like the automotive one, to deal or to anticipate with environmental regulation. Several studies have shown the correlation if not the causality between environmental regulation and patenting. For example Lanjouw and Mody (1996) show that increases in environmental compliance costs in United States, Japan and Germany are related to increases in patenting in environmental technology. As well Brunnermeier and Cohen (2003) find that innovation, as measured by the number of patents, was consecutive to increases in abatement expenditures which are used as a proxy for policy stringency. Taylor and al. (2003) show that patenting activity in SO₂ control began after the introduction of a regulatory regime by the 1970 Clean Air Act Amendments and the 1971 New Source Performance Standards. Regarding the automotive industry, Lee and al. (2005) show a close relationship between the magnitudes of patenting activity and a series of stringency levels for each of three pollutants considered (HC, CO, NO_x), with each increase in stringency leading to increased patenting activity over the period under study (1968-1998).

In fact patenting not only reflects the firm's technological position and its dynamism over time but is also an umbrella to protect the know-how and the very existence of a firm which could provide bargain power with other partners or guarantee a lead or first-mover advantage if regulation would come to move in the proper direction. This can be related to what Jacob et al. (2005) have called lead markets for environmental innovations, that is strict environmental regulations can create lead markets, enabling local firms to benefit from "early mover" advantages and so to export their innovations induced by local market conditions and national regulations. In this perspective, patents can thus represent a strategy to secure inventions potentially able to give an international competitive advantage.

II.2. Results: the diversification of patent portfolios

We first present the evolution of the cumulated total number of patents for each technology. Figure 3 shows a continuous increasing trend for ICEV and DE patents and the progressive increase in HV patents since 1999-2000 which finally catches up with EVB patents. The increase in FCV patents is significant since 2001 but remains relatively low compared with other technologies.

If we concentrate on patents applied by car manufacturers (figure 4), we observe that HV patents become superior to EVB patents since 2002. This is the consequence of the growing involvement of car manufacturers in the development of HV.

Figure 3

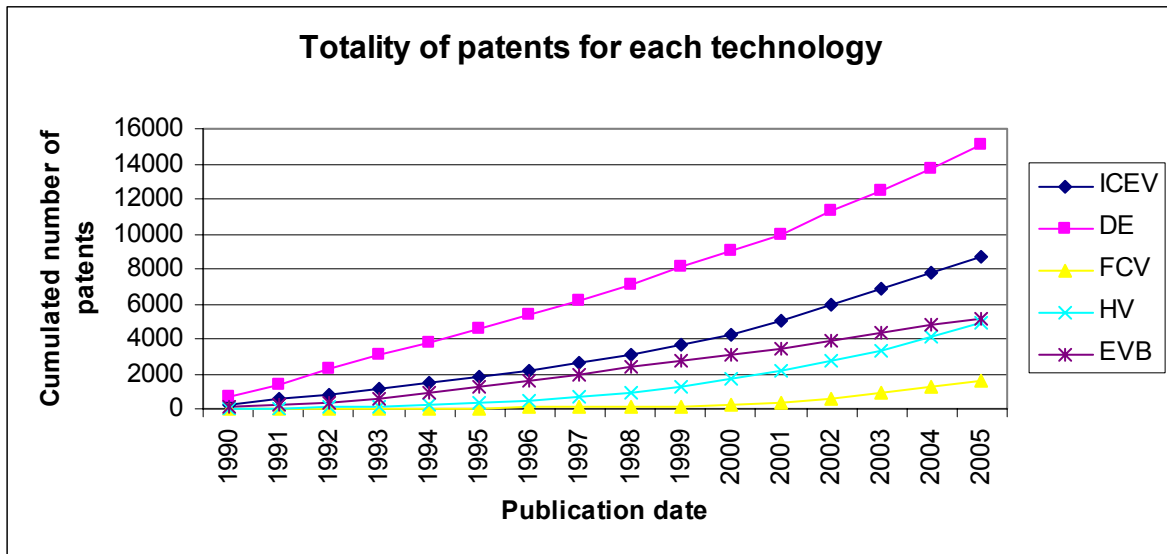
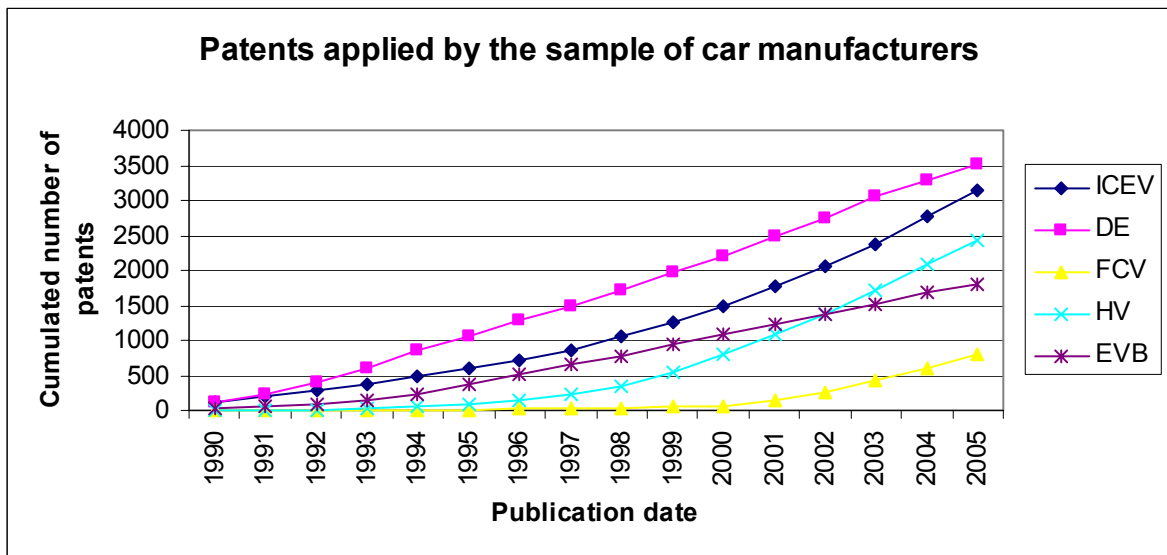


Figure 4



Moreover the increase in FCV patents is more manifest than the trend observed in figure 3. If we compare the share of car manufacturers in the total number of patents for each technology, we observe that this share is 57% and 45% for FCV and HV⁹ in 2005, while it is lower for the other technologies (40% for ICEV, 18% for DE and 36% for EVB). These results illustrate the strong involvement of car manufacturers in HV and FCV patents since 2002 and the shift in research focus from EVs to both hybrid and fuel cells vehicles. In spite of these advances in LEVs technologies, the dominant design is still under improvements, in particular the diesel engine. This is consistent with the fact that the conventional engine is far from being played out since it is still the core of innovative activities of car manufacturers. The analysis of the patent portfolios of car manufacturers confirms these arguments.

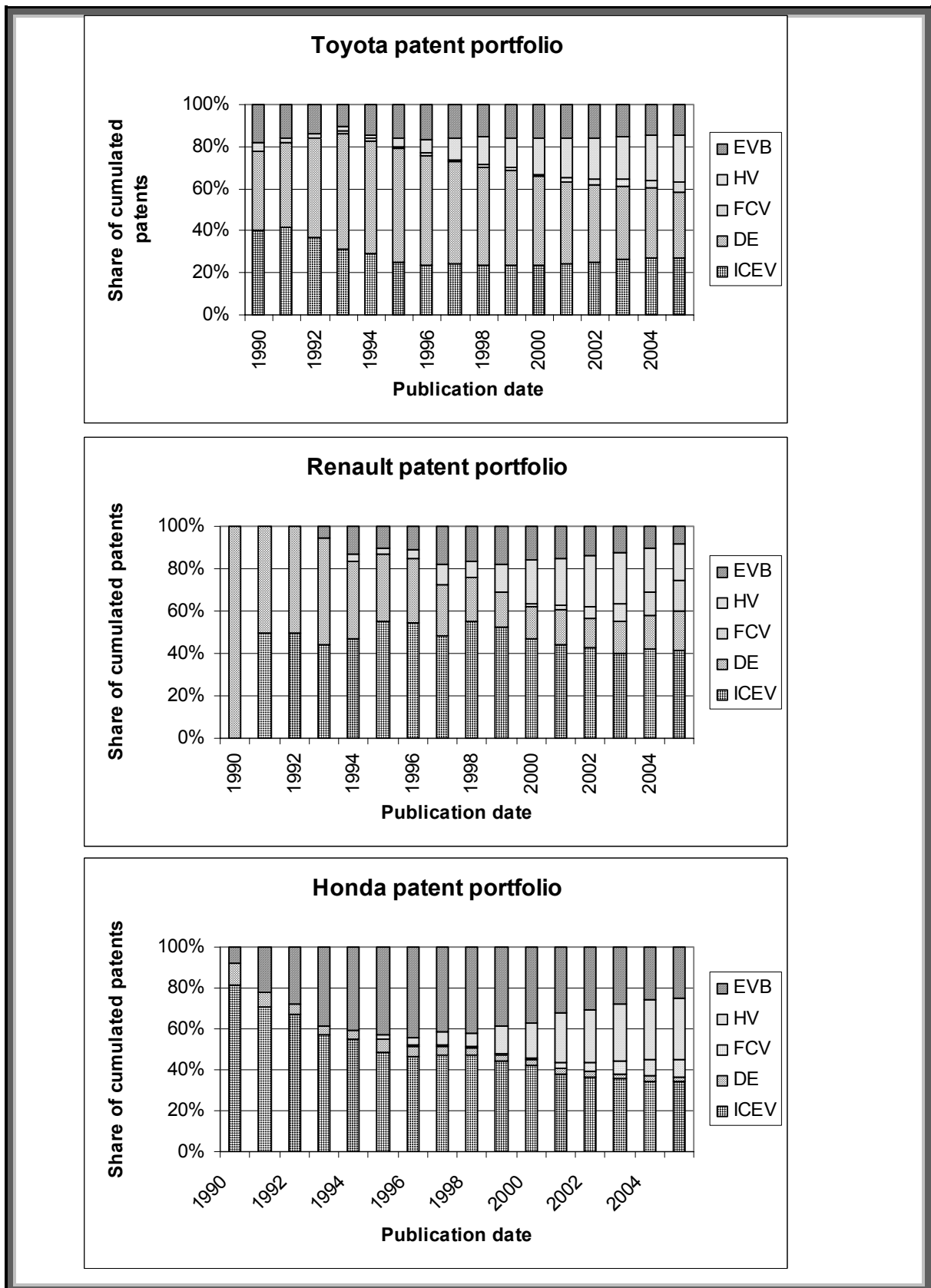
⁹ This share for HV amounted to 58% in 2003.

The evolution of patent portfolios of car manufacturers (cf. figure 5 and figure 1 in appendix) clearly shows the on-going diversification of these portfolios. This corroborates the results of Frenken et al. (2004) which show that the evolution of LEVs technologies is characterised as an explorative stage in which firms increasingly widen their patent portfolios. If we look at the patent portfolios in 2005, we observe that all the car manufacturers are involved in the five technologies under study. There is no sign of a significant specialisation of car manufacturers even if their portfolios are distributed differently among technologies. In the sense of Stirling (1998), we can say that there is an increase in the variety of technologies with differences in the balance of technologies¹⁰. For example, General Motors exhibits one of the most balanced portfolios of the sample in 2005, contrary to Hyundai or Volkswagen. The differences in the balance of portfolios are relevant to capture the strategy of firms.

The patent portfolios of firms confirm the strong dominance of the ICEV and diesel engine. Indeed more than fifty percent of the patent portfolio is still dedicated to the dominant design (ICEV+DE): for all the car manufacturers, except for Honda and General Motors, ICEV and DE represent more than 50% of the cumulated number of patents in 2005. What is specific to each car manufacturer is the sharing-out between DE and ICEV: for example in 2005, Toyota, GM and Volkswagen are characterised by a balanced distribution between ICEV and DE while Honda, as well as Renault to a lesser extent, are specialised on ICEV. On the contrary Hyundai exhibits a portfolio consisting in approximately 63% of DE patents. These results corroborate the continuous improvement of the established technology that goes on exploiting the increasing returns due to its status of dominant design. Moreover we can see that there are more and more environmental innovations in the field of ICEV and DE. This feature stresses that the established technology tries to compete on the environmental dimension. In terms of old-versus-new competition (cf. §I.3), it means that the old technology is also very active in the competition on the environmental function in order to be competitive with the new technologies.

¹⁰ More precisely, according to Stirling (1998), the variety corresponds to the number of technological options in the portfolio while the balance refers to the share of each option in the portfolio.

Figure 5: Patent portfolio of car manufacturers



Finally in this context of competition, the established technology tries to compete with the new ones on the environmental function, while the new technologies try to fulfil the genuine function of the dominant design they are supposed to replace.

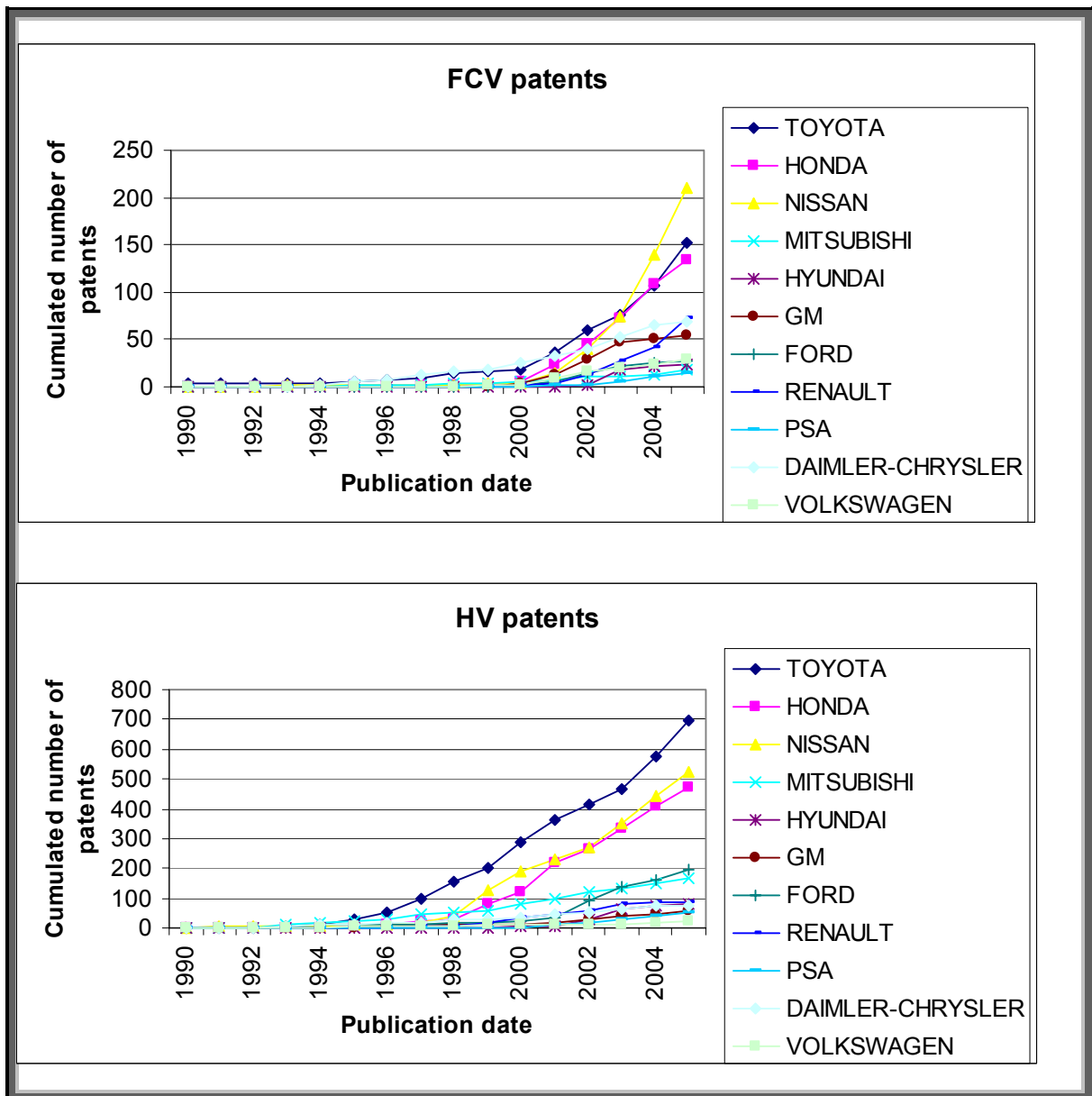
If we focus on LEVs patents, we observe that the share of EVB patents tends to decrease since the end of the 90s: this is particularly significant for Volkswagen and Honda¹¹. Toyota is an exception with a constant share dedicated to EVB patents over the period¹². We also notice that the share of HV patents is significantly increasing since 1995 with a first-mover advantage for Toyota in 1992. This result illustrates the argument according to which HV is now considered to be the most promising technology (cf. section 1) with a significant Japanese leadership. If we compare the portfolios of Japanese firms with the others, we can see that the Japanese ones are characterised by a relatively high share in EVB while the share of FCV is rather low. This is consistent with the fact that the Japanese car manufacturers are positioned on HV and EVB since they try to exploit spillovers between technologies and consider that the HV will strongly increase its market share in Japan and in US and that it is a determining transition step towards FCV.

If we focus on FCV and HV patents (figure 6), we can identify three groups of firms. Toyota, Honda and Nissan constitute the leading group for both technologies. For HV patents, Ford and Mitsubishi stand in an intermediary position while the six remaining car manufacturers of the sample are lagging behind. Concerning FCV patents, we observe the same pattern with an intermediary group composed of Renault, Daimler-Chrysler and General Motors. These patterns underscore the differences among countries: while the Japanese leadership on HVs is incontestable, the European car manufacturers are more reluctant to position on the hybrid technology. They still strongly bet on the conventional technology, in particular the diesel one, because they argue that the advanced diesel vehicles will exhibit environmental performances comparable to the ones performed by HVs for a very lower price. Moreover they do not consider HVs as a compulsory transition step towards FCV.

¹¹ In spite of this decrease, Honda is characterised by the highest share of EVB patents in 2005 (25%) in comparison to other manufacturers in the sample.

¹² Given the spillovers between EVB and HV, we can suppose that this feature is linked to the leading role of Toyota in HV.

Figure 6



Conclusive Remarks

The diversification of patent portfolios demonstrates that the competition between the LEVs is extremely active. In the future the progress of LEVs will depend on two factors: the evolution of performance of LEVs (in particular their price and range of use) and the evolution of regulation.

According to Maxton and Wormald (2005), the evolution of the share of engine technologies in the next thirty years will be characterised by a segmentation of the market. The share of advanced diesel vehicles will still increase while FCV, HV and natural gas vehicles will share less than 30% of the market and remain dedicated to niche markets.

According to Jacob and al. (2005), the evolution of regulation will be crucial. The US could be identified as a lead market for FCV due to the regulatory push in California. The market evolution of FCVs will depend on the diffusion of ZEV standards worldwide, but it seems unlikely that strict ZEV regulation will be introduced as such in other countries. As to HVs, Japan appears as a lead market able to widen to other countries. Finally advanced ICEVs are supported by the European car manufacturers. Especially direct injection technologies for diesel cars have become a market success because of the combination of fuel efficiency and high performances. The broad diffusion of advanced diesel cars will depend on the acceptance of the diesel technology abroad, but also on their ability to meet the strict US environmental standards.

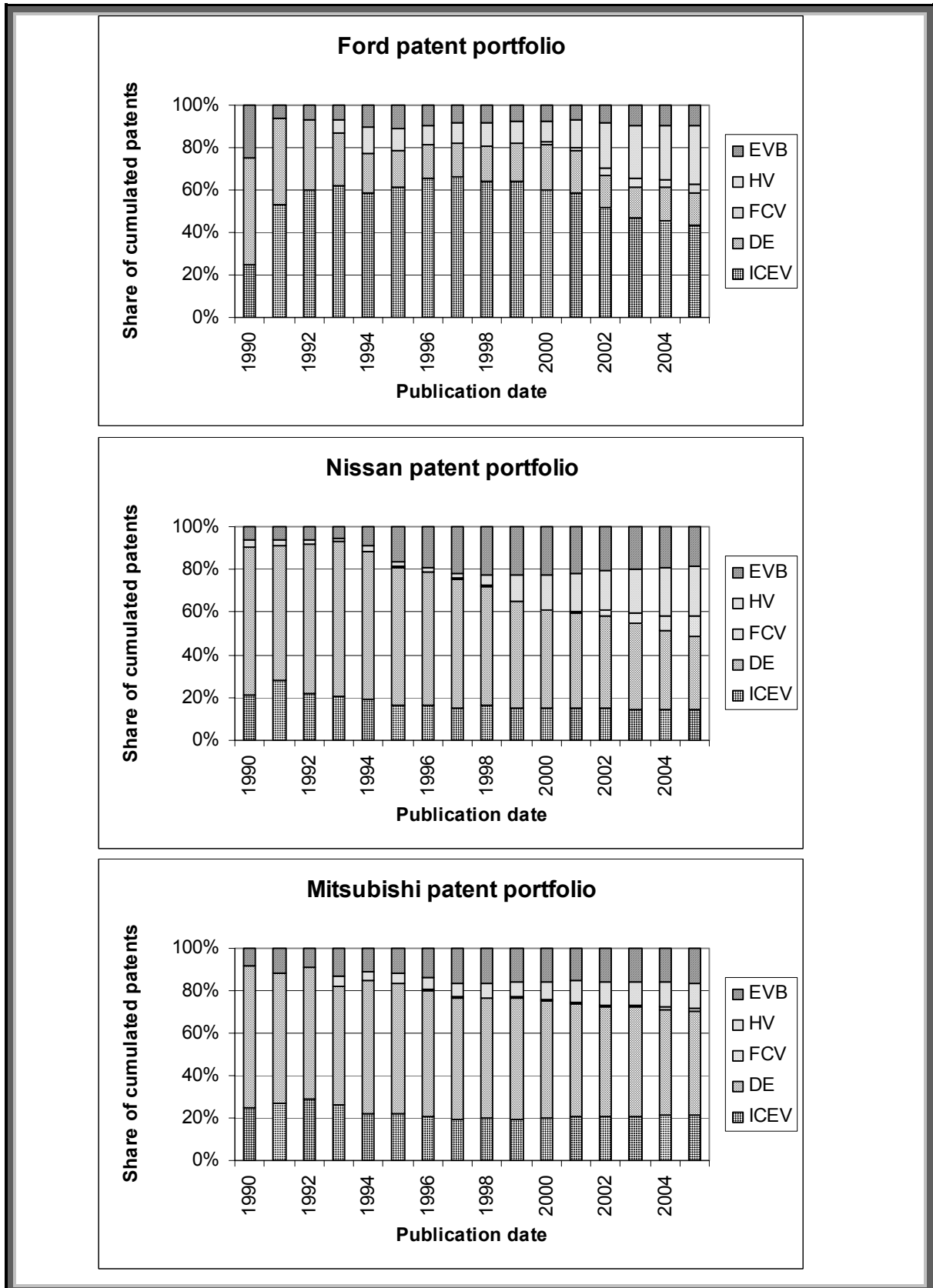
References

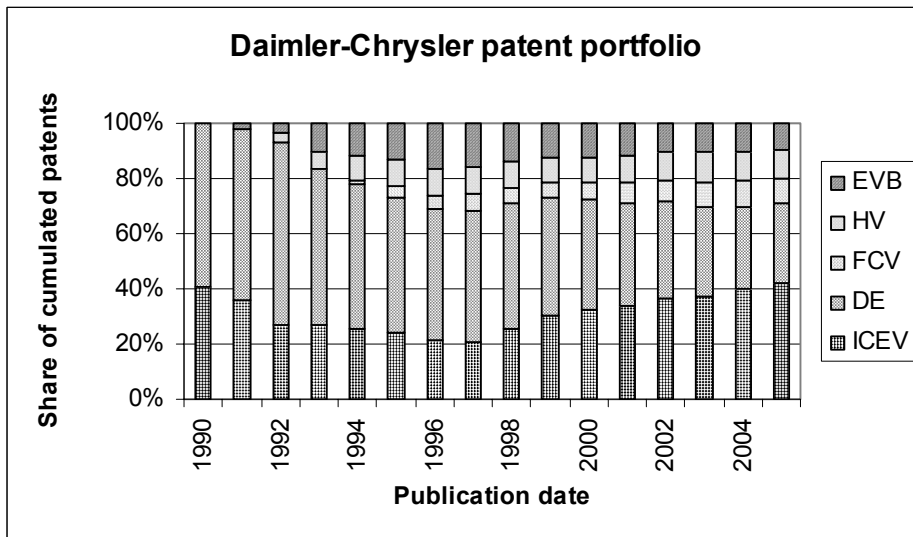
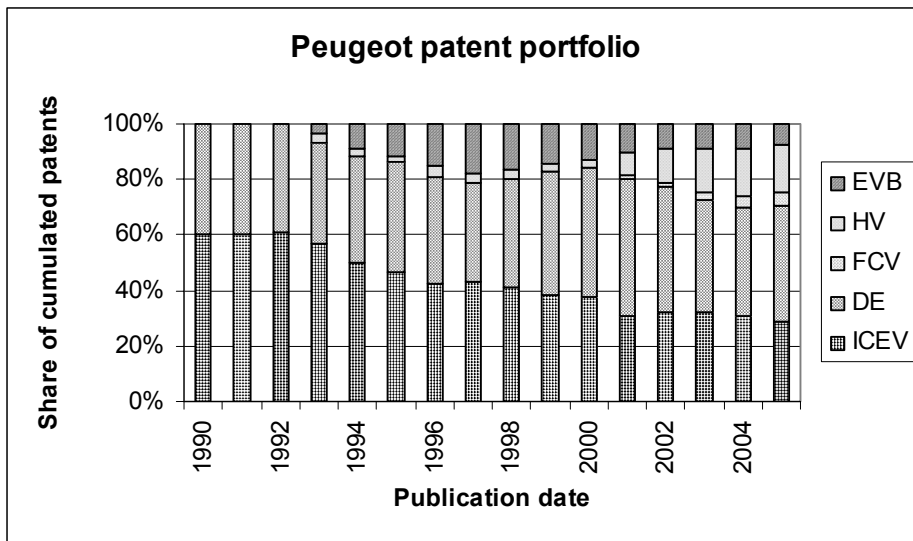
- Arthur W.B., 1988, "Competing technologies: an overview", in Dosi G., Freeman C., Nelson R., Silverberg g. and Soete L. (eds), *Technical change and economic theory*, London: Pinter, pp.590-607.
- Arthur W.B., 1989, "Competing technologies, increasing returns, and lock-in by historical events", *Economic Journal*, vol.99, pp.116-131.
- Brunnermeier S.B. and Cohen M.A., 2003, Determinants of environmental innovation in US manufacturing industries, *Journal of Environmental Economics and Management*, 45, pp.278-293.
- David P.A., 1985, "The economics of QWERTY", *American Economic Review*, vol.75, pp.332-337.
- ERTRAC, 2004, European Road Transport Research Advisory Council, *Strategic Research Agenda*, December 2004.
- European Commission, 2004, "Chapter 4: the European automotive industry" in *European competitiveness report 2004*, Commission Staff Working Document, SEC (2004) 1397, European Communities.
- Frenken K., Hekkert M. and Godfroij P., 2004, "R&D portfolios in environmentally friendly automotive propulsion: variety, competition and policy implications", *Technological Forecasting and Social Change*, vol.71, pp.485-507.
- Griliches Z., 1990, "Patent statistics as economic indicators: a survey", *Journal of Economic Literature*, Vol. 28, pp.1661-1707.
- Hekkert M. and Van den Hoed R., 2004, "Competing technologies and the struggle towards a new dominant design: the emergence of the hybrid vehicle at the expense of the fuel cell vehicle", submitted.
- Hoed R. v.d. and Vergragt P.J., 2003, "Technological shifts and industry reaction: shifts in fuel preference for the fuel cell vehicle in the automotive industry", Paper presented at 'Knowledge and economic and social change: new challenges to innovation studies' Conference, Manchester, UK, April 2003.
- Jacob K., Beise M., Blazejczak J., Edler D., Haum R., Jänicke M., Löw T., Petschow U. and Rennings K., 2005, *Lead markets for environmental innovations*, Physica-Verlag Heidelberg, Germany.
- Kemp R., 2005, "Zero emission vehicle mandate in California: misguided policy or example of enlightened leadership?", in Sartorius C., Zundel S. (eds), 2005, *Time strategies, Innovation and Environmental Policy*, Edward Elgar Publishing, Cheltenham, UK, Northampton, MA, USA.
- Lanjouw J. and Mody A., 1996, "Innovation and the international diffusion of environmentally responsive technology", *Research Policy*, Vol.25, pp. 549-571.
- Lee J., Veloso F., Hounshell D.A. and Rubin E.A., 2005, "Technology-forcing regulation and innovation: A panel data study in automotive emissions control", Under review at *Research Policy*.

- Lung Y., 2004, "Coordinating Competencies and Knowledge in the Auto Industry", Special issue of *International Journal of Automotive Technology and Management*, Vol.4, n°2/3.
- Maxton G.P., Wormald J., 2004, *Time for a Model Change*, Cambridge University Press.
- Oltra V. and Saint Jean M., 2005, "The dynamics of environmental innovations: three stylised trajectories of clean technology", *Economics of Innovation and New Technology*, vol.14 (3), pp.189-212.
- Sartorius C., Zundel S. (eds), 2005, *Time strategies, Innovation and Environmental Policy*, Edward Elgar Publishing, Cheltenham, UK, Northampton, MA, USA..
- Stirling A., 1998, "On the economics and analysis of diversity", *SPRU Working Paper* n°28.
- Taylor M.R., Rubin E.S. and Hounshell D.A., 2003, "Effect of government actions on technological innovation for SO₂ control", *Environmental Science and Technology*, 37, pp.4527-4534.

APPENDIX

Figure 1





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