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Technological trajectories in the automotive industry: are hydrogen technologies still a possibility?

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ABSTRACT

The integration of hydrogen technologies in the automotive industry as an option to cope with environmental issues has typically attracted significant attention among politicians, academics, and the media. After the recent "hydrogen hype" this interest in hydrogen technologies highlights the need to fully understand to what extent this sector is being pushed by new inventions. This paper presents a worldwide patent analysis of hydrogen technologies in the automotive sector. The study has been performed using a novel methodology by assessing trends of patents between 1990 and 2010 and their citations. As a result, we emphasize that the interest in hydrogen technologies has not declined over time and is mainly focusing on a small number of niches, although competing alternatives, such as electric vehicles, capture greater interest. Moreover, citation trends provide further insight into the development prospects of fuel cell and storage technologies as a point of convergence of multi-sectorial investments and, consequently, of potential R&D strategies in the automotive sector.

1. Introduction

To date, hydrogen technologies (HTs) are considered by several studies to be potential components of future energy systems (Amer and Daim, 2010). In particular, HTs have received a great deal of attention among politicians, academics and the media, especially between 1990 and 2006, when HTs were integrated into the automotive industry as an option to cope with its environmental impact (i.e. atmospheric emissions reductions, fuel consumption and noise) (Bakker et al., 2009). Despite energy balance assessments unanimously showing a poor life cycle energy performance of hydrogen-based mobility, studies on HTs are still part of the agenda of industries, research bodies and policymakers, in virtue of hydrogen's potential in the development of renewable energy storage, energy supply security and decentralization of the energy system.

There are, however, many unanswered questions about the technological life cycle of HTs. One of these surrounds the "chicken-egg" problem of whether the lack of infrastructures is the major barrier to alternative to vehicles that run on alternative fuels, or vice versa (Browne et al., 2012). Other important issues also play a role, such as the competition between hydrogen vehicles and fossil fuel internal combustion engines (ICEs) in traditional market segments, as well as the "technology race" (Ball and Wietschel, 2009; Browne et al., 2012) within the sector of electric vehicles in green market niches.

Within this context, after the recent "hydrogen hype," patent dynamics of HTs associated with the automotive industry are becoming quite relevant and call for deeper understanding (Bakker, 2010a). The aim of the present study is to analyze the worldwide trends in hydrogen inventions through a life-cycle perspective so as to improve understanding of the following: 1) the current relevance of HTs for the automotive industry and 2) current paths in the process of diversification of HTs. The "Background" section of this paper presents an overview of different approaches to patent analysis and describes the peculiarities of HTs in the automotive industry as the research setting. World-wide HT-related invention trends in the field of alternative fueled vehicles are here presented as a relevant issue for both methodology development and practical implications. The "Methodology" introduces a novel methodology for patent analysis based on trends and citations by describing the procedures and tools implemented. The "Results and Discussion" section shows the practicability of this methodology and highlight the heterogeneous vitality of different HTs in the automotive sector. Finally, we provide managerial and policy

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implications related to the development of HTs as an option for alternative fuel vehicles (AFVs).

2. Background

The use of patents as sources of information about technological progress has both advantages and disadvantages. The main advantage is that patents provide long-term and detailed technological information. The main disadvantages are that: simple patent counts do not take into account differences in technological quality; many patented inventions do not lead to innovations (i.e. are not applied) and the propensities to patent an invention may differ between sectors and firms (Verspagen, 2007).

Grounding on this premise, patents provide reliable information about trends in technologies and research and development (R&D) activities in order to support competitive analysis and technologies trend analysis (Abraham and Morita, 2001; Liu and Shyu, 1997). Therefore, analysis of patent data is considered a valuable method to assess technological changes and facilitate strategic planning efforts (Abraham and Morita, 2001).

Patent analysis can support the study of technological and economic development (Penrose, 1951; Taylor and Silberston, 1973), the assessment of R&D activities in a national and international context (Abraham and Morita, 2001; Paci and Sassu, 1997), analysis of the level of technological development in a particular sector from the perspective of firm policy (see Archibugi and Pianta (1996) and Basberg (1987) for patent analysis as a means to measure technological change; see Mogee (1991) and Liu and Shyu (1997) for patent analysis as a support for strategic planning), of technological strengths and weaknesses of competitors (Narin and Noma, 1987), and of foreign markets (Shipman, 1967).

Despite being a meaningful source of information, in the AFV sector there is a lack of studies which use patent analysis to define worldwide (historical) technological trends over a long period of time in order to provide information for establishing technological strategies in firms and policies. Geographical coverage, evolutionary nature and technology intensity are some of the characteristics that make AFV sector a suitable research setting for studying the following:

- Does a worldwide patent analysis represent a handy tool to define worldwide technological trends from a life cycle perspective?
- Do these technological trends provide firms and policymakers with useful information about potential directions for technology development?

Among AFV alternatives, HTs in the automotive industry have been in an "era of ferment" during which new technologies, in every stage of the supply chain (i.e. hydrogen production, storage, transport and conversion), have been developed and introduced into the already mature industry (Anderson and Tushman, 1990). Recent changes in attitude towards alternative fuels and HTs in the automotive industry have been triggered by the volatility of fuel prices, more stringent environmental legislation, new market demands and the maturation of new technologies (Orsato and Wells, 2007; van den Hoed, 2007; Magnusson and Berggren, 2011). In fact, in the United States the number of AFVs in use increased by 39.5% in the 2005–2009 period (U.S. Census Bureau, 2012).

In this sector, the development of alternative powertrain technologies necessarily induces the replacement of the existing ICE with a different system and requires new and massive investments (Zapata and Nieuwenhuis, 2010). Therefore, the automotive industry is facing uncertainty regarding the prospects, evolution and uptake of existing AFVs technologies (Contestabile et al., 2011) (i.e. flex-fuel vehicles, Hybrid Electric Vehicles, Electric Vehicles, Hydrogen Fuel Cell (FC) Vehicles, Hydrogen ICE vehicles, Liquid Petroleum Gas vehicles and Compressed Natural Gas vehicles). Each type of AFV technology can produce a different innovative effect on the ICE powertrain and the socio-economic environment (Hekkert et al., 2005; Sierzchula et al., 2012). In particular, HTs as possible options among AFVs have faced an overestimation in terms of cost reductions and driving range in the automotive industry during the previous decade. This overestimation, known as the "hydrogen hype", produced disappointment which fostered the development of other AFVs such as Electric Vehicles (Bakker, 2010a). In fact, the prototypes of hydrogen passenger cars compared to current passenger cars are underperforming in terms of economic and technical efficiency (Romm, 2004). Therefore, world-wide HT-related invention trends are worth analyzing because HTs, including the different ways of production and use of hydrogen in cars, might be "prospective rather than actual technological options" (Bakker et al., 2012). In fact, car manufacturers have maintained diversified patent portfolios with different technological options for HTs (Bakker, 2010b; Oltra and Saint Jean, 2009) and have developed cross-company collaborations to share the development costs of HTs (e.g. BMW and Toyota; Daimler, Nissan and Ford; Honda and General Motors).

Based on the above considerations, HT patent data represent a suitable research setting for both testing tools for the analysis of long-term invention trends and advancing knowledge on sectorial AFV strategies.

3. Methodology

Our research design is based on patent data. It employed citation-based patent measures as a source of information on technological life cycles.

Having set the focus on the evolution of a specific technological field (i.e. HTs in the automotive sector), USPTO-granted patents represent a sound source of data (Pilkington, 2004). The USPTO dataset is considered comprehensive when it refers to relevant inventions. In fact, it is recognized that there is a relatively higher cost of patent applications in the US compared, for instance, to Japan. As a result, Japanese firms are known to patent a great deal in their own country for decoy reasons, but have more difficulty in patenting in the US (van den Hoed, 2005).

Moreover, the US patent law requires applicants to disclose prior art related to the invention in question ("duty of candor") (von Wartburg et al., 2005). Michel and Bettels (2001) show that US patent applications require many more references than the applications of non-US patent offices.

Since the HTs are rapidly evolving and a patent has a limited life, nominally a maximum of 25 years in the US (Pilkington, 2004), a time span of 20 years for this study (1990–2010) has been considered as consistent with the goal of the analysis. The selection of the time boundary is also justified by the growth in technological variety and organizational competition, which coincides with the change in environmental policy implemented in the 1990s (e.g. the Californian Air Resources Board in 1990). The period 2011–2013 is not considered because in patent citation analysis the tendency for new patents to be less cited than old ones could prove to be a limitation when analyzing the recent years (Yoon and Kim, 2011).

The authors have developed a set of software instruments on an open source environment (i.e. Perl, Lazarus and Gnuplot under Linux) to assist with the patent search. The core of the set is a program capable of automatically interrogate major patent search engines such as FreePatentsOnline and Espacenet. Starting from a list of keywords and a set of options, the program conducts as many interrogations as needed to perform the requested analyses. The program automatically produces data, tables and graphs, and prepares html pages to navigate through data and graphs, thus aiding in the examination and elaboration of the results of the analysis. Other programs complete the suite to allow the analyst to manipulate the chosen keywords and search options, and to properly handle the graphic outputs.

We used implicit knowledge of domain experts to lay the foundations for developing further insights through a computer-based approach, which analyzes explicit knowledge from patents (Kajikawa et al., 2008). In details, from an operational point of view, we first identified and verified a set of sectorial keywords in relevant publications (e.g. Ball and Wietschel, 2009). In doing so, we integrated bibliometric process analysis utilizing expert opinions as a standard practice (Watts and Porter, 1997). We conducted one-on-one interviews with 4 experts from universities and 15 experts from HT companies involved in the "Filiera H2" project[1] to identify suitable keywords describing HTs in the automotive sector. These keywords included HTs associated with powertrain but also with other components related to the hydrogen supply chain in the automotive sector (see Table 1).

We conducted the analysis of worldwide patent trends associated with HTs in the automotive industry through a life cycle perspective in four phases.

First, we counted the number of patents through searching occurrences of keywords both in the title of patents (i.e. a delineation approach that is expected to be very accurate) and in the abstract of patents (i.e. a delineation approach that less accurate but that allows the analysis of a greater number of records). The two delineation approaches were used in order to compare and confirm the results and interpretations (i.e. to improve the reliability of findings).[2]

Subsequently, we compared the level of research activities related to hydrogen vehicles and electric vehicles by using all the keywords related to HTs in the automotive industry (Table 1) and the keyword "electric vehicle" in the above-mentioned patent delineation approaches. Therefore, after cleaning neutral inclusions (i.e. patents that refer to "electric vehicles" and that contain also HT-related keywords), a strong $A' < B'$ relation was tested, A' being the number of patents resulting from the search for overly generic keywords ($A' > A$) in the field of HTs (i.e. keywords that refer to components/processes that are not exclusive to the automotive sector) and B' being the number of patents resulting from the search for overly specific keyword ($B' < B$) in the field of electric vehicles (i.e. there are not keywords that do not refer explicitly to electric vehicles), so that $A' > B'$ implies $A < B$ (see Fig. 1).

Third, we analyzed the citations over the time of yearly patented inventions delineated, again, by the presence of keywords in the title or in the abstract. The analysis of the citations was carried out because patents which are cited more often have a higher relevance in the drawing of the evolution of the technological pathway (Godoe and Nygaard, 2006). In fact, the non-random nature of citations could provide insights into the directions in which a sector might evolve (i.e. reflect the systemic influences between inventions). Furthermore, citations provide more information about a patent's technological and economic value (Trajtenberg, 1990).

A reference to a previous patent indicates that the knowledge of that patent was in some way useful to develop the new knowledge described in the citing patent. Thus, highly influential inventions are expected to achieve high numbers of citations per year and total citations (i.e. the area under the curve which has the axes of time and number of citations). Of course, the higher the number of patents that build on previous inventions, the sooner the previous inventions will be phased out by the new ones.

Finally, in our analysis we took citations and coherent citations into account, the latter being the patents that, beside being cited by one patent, have the same keywords as the citing patent (i.e. can be referred to the same technological domain of the citing patent).

Since a multitude of factors concur in determining the level of influence of a technology (e.g. interlocked lock-ins, integration with other technologies, etc.), more complex behaviors than the ones reported in Fig. 2 are expected.

In addition, following the approach adopted by other studies (von Wartburg et al., 2005; Albert et al., 1991), meaningful interpretations are anticipated from the integration of the results of patent analysis with technical analysis. The technical analysis is carried out by employing expert opinions and reviewing the literature on HTs in the automotive industry. Regarding the expert opinions, we informed experts previously involved in the selection of keywords about the results of patent analysis and we gathered their comments (i.e. in terms of agreement/disagreement with our interpretations).

Owing to the potential distortion caused by the lack of sufficient time for developing R&D activities inspired by previous inventions, the results are limited to the 1990–2010 timeframe.

Table 1
List of keywords.

Phase	Keyword
Production	Hydrogen shift reactor
	Hydrogen catalysts
	Hydrogen reformer
	Hydrogen electrolyser
Storage	Hydrogen storage
	Hydrogen pressure vessel
	Hydrogen storage vessel
	Hydrogen pressure gauge
	Hydrogen hydride
Use	Hydrogen ignition
	Hydrogen spark ignition
	Hydrogen ECU
	Hydrogen ICE
	Hydrogen power-train
	Hydrogen PEM
	Hydrogen bipolar plate
	Hydrogen fuel cell
	Hydrogen car
	Hydrogen tank
Control	Hydrogen carbon monoxide
	Hydrogen poisoning
	Hydrogen electrochemical sensors
	Hydrogen sensors

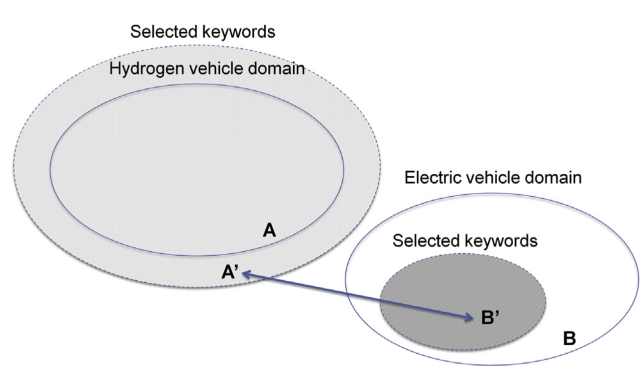

Fig. 1. Comparison between hydrogen and electric vehicle domains.

[1] The "Filiera H2" project, founded by the Tuscany Regional Administration, aims to support local governments in the analysis of local resource-based paths to the development of a hydrogen energy supply chain in the transportation sector.

[2] Section 4 presents a selection of graphs that have been generated and studied in this research. The selection of graphs depicting delineations based on titles or abstracts is made according to a readibility criteria (i.e. selection of the graph that provide a clearer representation of the trend that is discussed).

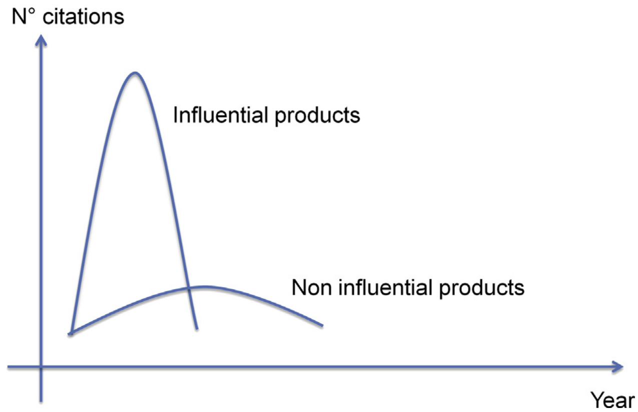

Fig. 2. Comparison of influential and non-influential product citation curves.

4. Results and discussion

Boundaries between generic and vehicle-oriented technologies are not sharp by nature. The use of a broad set of keywords allowed us to learn more about the dynamics that could directly or indirectly impact the use of HTs in the automotive sector.

4.1. Polarization over storage technologies and FCs

The increase in the number of sectorial R&D outputs proves that HTs in the automotive sector are still viable options despite the scores of projects and prototypes systematically failing to gain automotive market shares.

Over the last 20 years, trends have shown that there is a certain polarization over both storage technologies and FCs, the latter being associated with faster growth. Based on the considerations of Chen et al. (2011) and Mock and Schmid (2009) about the higher maturity of FCs with respect to production and storage technologies, our data suggest that the order of magnitude in terms of research intensity is nearly the same for each component (see Fig. 3).

The growth of hydrogen FC counts is higher in the abstracts than in the titles. This confirms the impression of sectorial experts that FCs are in the phase of integration with other related technologies (i.e. FC technologies under transfer into complex systems) (see Fig. 4). Such effect is less evident for production and storage technologies, a domain where market diversification prevails over product concentration (Bakker, 2010a,b).

Patent dynamics associated with FC systems prevail over ICEs. Despite the interest of relevant manufacturers in options that are near commercialization, such as hydro-methane ICEs (e.g. the concept cars Fiat Panda Aria, Iveco Ecodaily, etc.), experts remark that the larger attraction of investments in FC systems could also be caused by the sharing of several technological platforms with electric vehicles. In turn, electric vehicles have benefitted from exogenous stimulus (Dijk and Yarime, 2010) and are probably the most promising option for the short-term commercialization of AFVs.

4.2. Electric vehicles and hydrogen vehicles: a clear trend

The comparison of patent dynamics between electric vehicles and hydrogen vehicles confirms that electric vehicles are attracting the lion's share of green-oriented R&D in the automotive sector (Sierzchula et al., 2012) (see Fig. 5). Indeed, the annual number of patents related to electric vehicles is on average more than twice that of the patents related to all the keywords selected for HTs in the automotive industry. This is important because a large number of technologies that have recently developed within the classes of Electric Vehicles and Hybrid Electric Vehicles have considerable spill-over effects on the future development of FC Vehicles.

4.3. Life cycle of HT patents

Useful insights emerged from the analysis of the life cycle in the research and development of specific components (i.e. the ones described by selected keywords) through the investigation of patent citations (i.e. search in the title or abstract). The annual number of citations of patents per year shows rapid growth in the last few years for all the investigated keywords, but some HTs have more significantly increasing trends. These findings confirm the relevant effects of other R&D activities (e.g. those on telecommunication or medical equipment) on HTs. Beside ICE technologies (see Fig. 6), that have been pushed by FIAT group, a relevant growth in numbers emerges for "hydrogen tank" (see Fig. 7) when referring to the search of keywords in the abstract. In both cases, 1998–2004 seems to be the period in which the most influential patents have been registered (i.e. the lines that start in each of these years achieve a high number of citations per year).

While the most influential patents for "hydrogen tank" are still widely cited, and newer patents have yet to be cited, we found a sharp peak of citations for "hydrogen ICE" in 2007. This could reinforce the interpretation that, without specific support (e.g. research programmes), hydrogen ICE will play the role of a latent option. It is worth reiterating that Frenken et al. (2004) argue that the dynamics of investment in a variety of alternatives are particularly important also because the substitution of conventional car technology with a new automotive propulsion technology may lead to a premature lock-in of suboptimal technology.

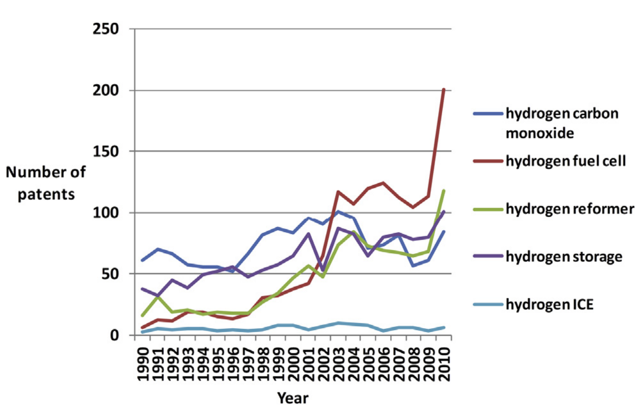

Fig. 3. Annual number of patents ("hydrogen" + keywords in abstract).

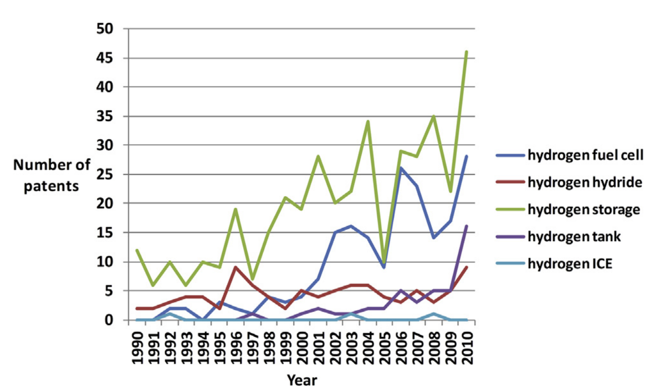

Fig. 4. Annual number of patents ("hydrogen" + keywords in title).

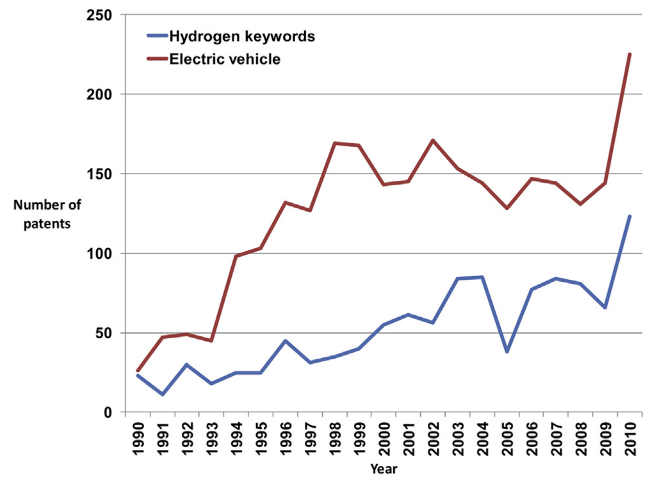

Fig. 5. Annual comparison between "electric vehicle" and hydrogen keywords (all keywords in title).

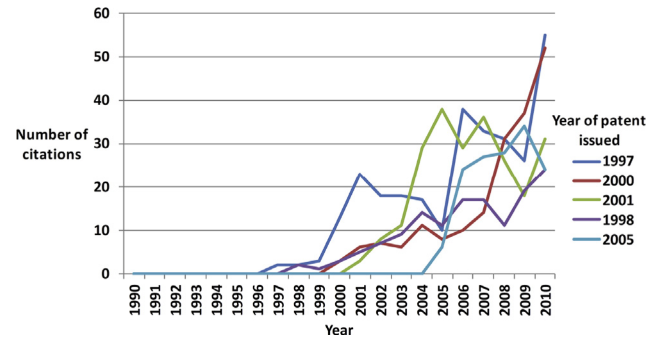

Fig. 7. Number of citations of patents issued in a specific year ("hydrogen" + "tank" in abstract).

With regard to patent citations obtained by searching keywords in the title, a particularly rapid growth was recorded for FCs (see Fig. 8). In this case, the most influential patents were registered between 2000 and 2002, with contributions that are also widely cited today. This is not surprising if we consider that FCs have potential applications, not only in the automotive sector, but also in other sectors such as telecommunications, health and food. Furthermore, these findings confirm the technological maturity and durability of FCs (Eberle et al., 2012).

The same plot for "hydrogen storage" (see Fig. 9) shows a steady behavior of patents and related citations over time. After a peak of citations lasting 4–8 years, influential patents give way to new generations of patents (i.e. prevalence of technological alternatives over their applications), and so on. Accordingly, HTs for storage represent great uncertainties and challenges for investors.

Taking into account the number of patent citations, the development of FC and storage technologies has been shown to be more relevant than that of other HTs.

Figs. 10 and 11 compare the annual number of patents with their corresponding total number of coherent citations (i.e. the area under the "citations of yearly patent" curves) respectively for FC and storage technologies. With reference to the coherent citations, the charts highlight that in recent years, after a peak in 2000–2002 related to aforementioned "hydrogen hype," investors have championed the exploration of new pathways.

Lastly, useful information about these new pathways can be obtained from the comparison of citations and coherent citations for FC and storage technologies (see, as an example, Fig. 12). The experts' interpretation of the low rate of coherent citations for FCs refers to the sufficient maturity achieved by this technology and, consequently, to the prevailing efforts towards improving system integration. On the contrary, the higher rate of coherent citations for storage technologies indicates that inventors are still exploring possible evolutions of a variety of alternatives (i.e. these technologies have not achieved adequate maturity to enter the integration stage of the system over the years).

5. Conclusions

This study aimed to verify whether inventions in HTs connected to the automotive industry still substantially influence the current paths in the process of diversification among AFV technologies.

Even though the R&D activities on AFVs have been dominated by electric technologies since the "hydrogen hype", our analysis of the global trends of patenting activities between 1990 and 2010 confirms that the interest in HTs in the automotive sector has not declined, mainly because of the proliferation of studies on FC and storage technologies.

The analysis of patent citations highlights the great development potential for FCs in the automotive industry, in addition to other sectors (e.g. telecommunications), which are currently planning many applications associated with FCs. Furthermore, the interesting dynamics of patent citations for storage technologies show significant efforts in confronting the big issue of refueling for

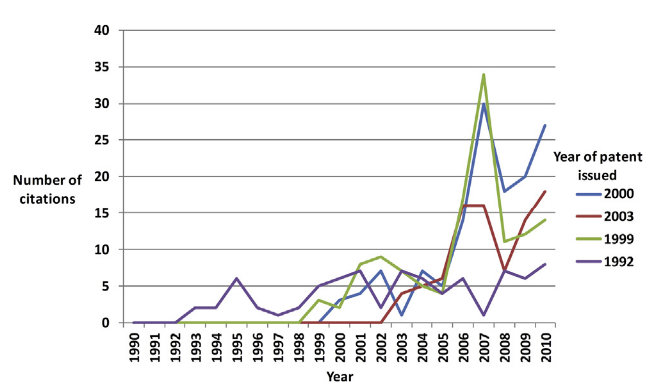

Fig. 6. Number of citations of patents issued in a specific year ("hydrogen" + "ICE" in abstract).

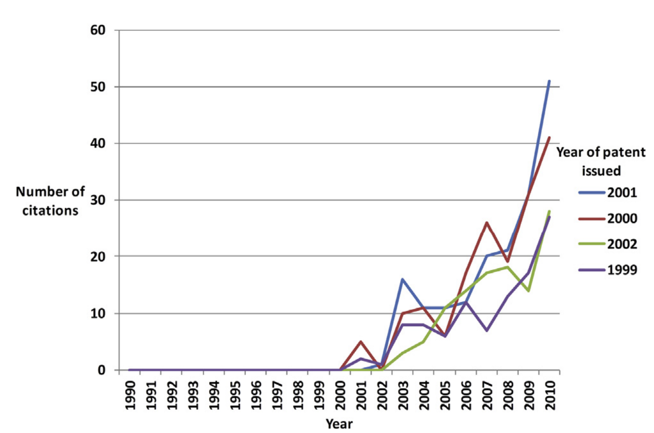

Fig. 8. Number of citations of patents issued in a specific year ("hydrogen" + "fuel cell" in title).

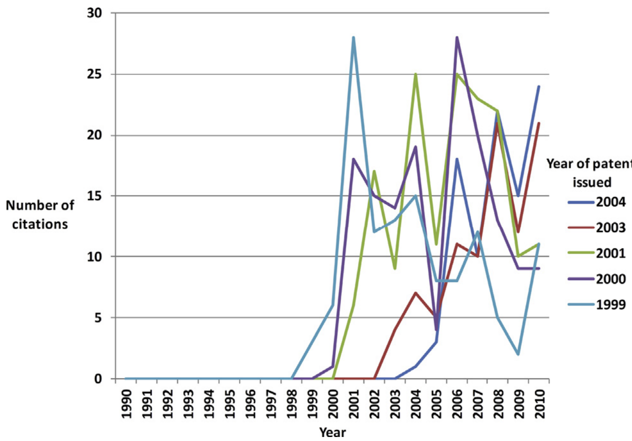

Fig. 9. Number of citations of patents issued in a specific year (“hydrogen” + “storage” in title).

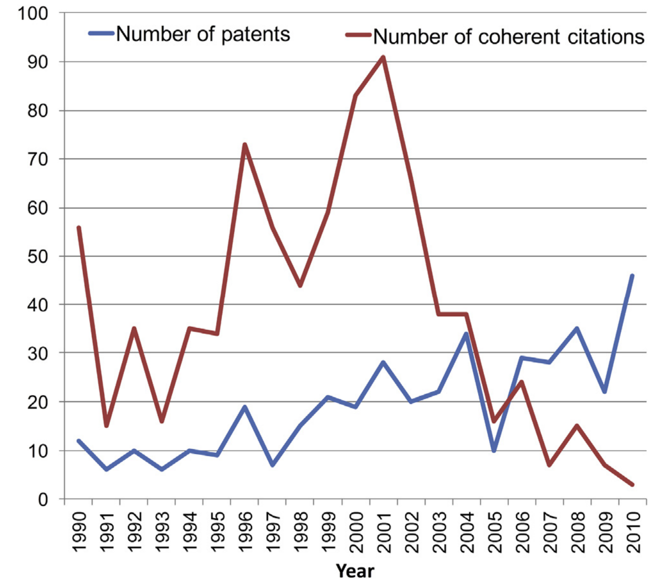

Fig. 11. Number of patents (“hydrogen” + “storage” in title) and corresponding coherent citations.

hydrogen ICE and FC vehicles. Therefore, FCs and hydrogen ICEs are still developing as the two main applications of HTs in the automotive industry, but with different intensities. In fact, there are fewer hydrogen ICE inventions than FC inventions because FC technologies are enhanced by their strong complementarity with electric vehicles. This evidence confirms the presence of a technological diversity in the automotive sector designed to improve existing competences and acquire new complementary knowledge. Furthermore, the trends described above appear to be driven by research activities carried out in the early 2000s during the beginning of the automotive sector’s “era of ferment” and the “hydrogen hype”. During that period, the first spark of interest in AFVs (clearly shown by electric vehicle trends) was coupled with the registration of the most influential patents. In fact, these patents have the highest number of citations, even when considering the influence of time in the most recent years.

These findings provide some managerial and policy implications. From a managerial point of view, this analysis of worldwide patent dynamics through patent citations can integrate and strengthen scientific knowledge on the dynamics of HTs in order to support automotive firms in the definition of their R&D strategies. Practitioners are encouraged to apply the proposed methodology for the assessment of the technological life cycle because of its rigor and simplicity. From a policy point of view, this study highlights the importance of a multi-sectorial framework of policy measures, such as energy and mobility policies, in order to foster AFVs and in particular HTs. Since the peak of activities in HTs during the early 2000s has produced a number of influent inventions and multi-sectorial spill-overs, interventions should be considered in order to ensure that the momentum is maintained.

However, some limitations of this study must be stressed. First of all, the synergies between our data and previous studies are fundamental to the development of a robust interpretation of patent trends. This means that such an approach cannot be considered a stand-alone piece of work. Additionally, a deeper semantic network analysis would be useful in order to gain a better understanding of the nature of the peaks during the early 2000s. Finally, inter-temporal trends could be more explanatory if a broader set of green vehicle options were studied.

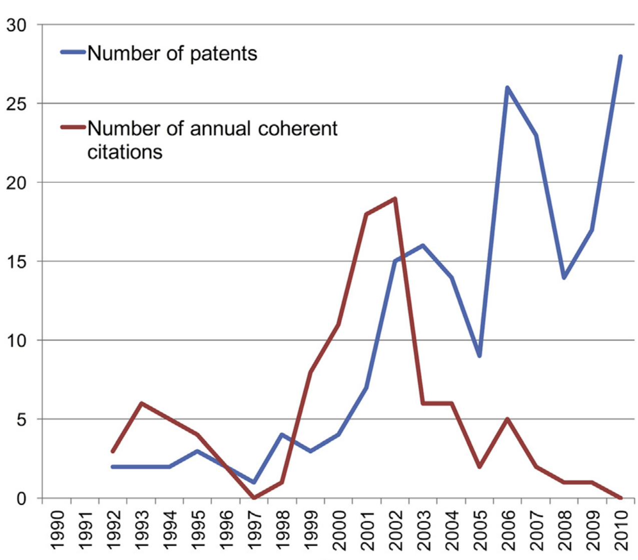

Fig. 10. Number of patents (“hydrogen” + “fuel cell” in title) and corresponding coherent citations.

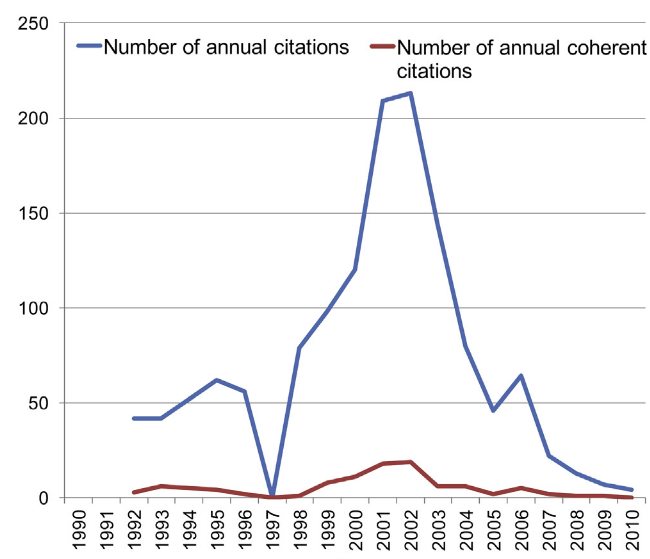

Fig. 12. Number of generic and coherent citations (“hydrogen” + “fuel cell” in title).

APPENDIX

Table 1
Annual number of patents ("hydrogen" + keywords in abstract)

Keywords	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
"Hydrogen" + "fuel cell"	6	12	11	19	19	15	13	17	30	32	37	42	64	117	107	120	124	113	105	114	201
"Hydrogen" + "reformer"	16	31	19	20	17	19	18	18	27	34	46	56	47	73	84	72	69	67	64	68	118
"Hydrogen" + "storage"	37	32	45	38	49	52	55	47	53	57	64	82	53	87	82	64	80	82	78	80	101
"Hydrogen" + "carbon monoxide"	61	70	66	57	55	55	52	66	81	87	83	96	90	101	96	71	73	81	56	61	84
"Hydrogen" + "hydride"	27	25	41	23	31	30	35	42	26	34	30	42	47	37	31	32	25	27	32	32	42
"Hydrogen" + "sensors"	8	13	11	19	21	17	21	16	16	25	21	21	28	40	24	30	32	42	39	25	40
"Hydrogen" + "tank"	4	4	12	9	5	13	6	22	12	21	16	28	18	33	30	31	31	29	28	31	35
"Hydrogen" + "metal hydride"	15	14	26	12	21	18	20	31	21	21	23	32	32	28	17	16	14	19	16	16	24
"Hydrogen" + "ignition"	6	7	6	8	7	14	7	11	4	6	6	11	13	15	14	12	18	8	7	7	9
"Hydrogen" + "shift reactor"	2	0	0	0	3	6	2	1	2	1	6	3	7	11	5	8	5	3	12	8	9
"Hydrogen" + "pressure vessel"	6	10	13	8	8	13	7	11	14	15	10	9	5	7	10	8	4	12	13	6	8
"Hydrogen" + "ICE"	2	5	4	5	5	3	4	3	4	8	8	4	7	10	9	8	3	6	6	3	6
"Hydrogen" + "PEM"	0	0	0	0	0	0	0	0	0	2	4	4	4	8	8	5	4	4	2	5	6
"Hydrogen" + "poisoning"	8	4	4	9	3	9	2	2	4	7	5	4	7	11	4	5	3	3	2	6	6
"Hydrogen" + "electrochemical sensors"	0	0	1	3	1	1	4	1	3	3	2	2	3	6	3	0	1	4	3	1	3
"Hydrogen" + "storage vessel"	0	1	1	2	2	3	1	2	6	6	4	5	1	4	3	5	8	7	5	3	3
"Hydrogen" + "car"	1	5	1	2	2	2	1	5	2	3	1	2	0	0	4	1	3	1	0	2	1
"Hydrogen" + "ECU"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
"Hydrogen" + "pressure gauge"	1	1	1	0	0	1	1	0	0	0	0	0	1	2	0	4	1	2	2	0	1
"Hydrogen" + "bipolar plate"	2	0	1	1	0	0	0	0	2	1	3	1	1	1	2	1	0	1	0	1	0
"Hydrogen" + "electrolyser"	0	0	1	1	0	1	1	3	0	1	2	0	0	1	0	0	0	0	0	0	0
"Hydrogen" + "powertrain"	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0
"Hydrogen" + "spark ignition"	0	0	3	1	1	5	2	3	1	0	1	0	2	1	2	0	2	1	0	0	0

Table 2
Annual number of patents ("hydrogen" + keywords in title)

Keywords	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
"Hydrogen" + "storage"	12	6	10	6	10	9	19	7	15	21	19	28	20	22	34	10	29	28	35	22	46
"Hydrogen" + "fuel cell"	0	0	2	2	0	3	2	1	4	3	4	7	15	16	14	9	26	23	14	17	28
"Hydrogen" + "tank"	0	0	1	0	0	0	0	1	0	0	1	2	1	1	2	2	5	3	5	5	16
"Hydrogen" + "hydride"	2	2	3	4	4	2	9	6	4	2	5	4	5	6	6	4	3	5	3	5	9
"Hydrogen" + "reformer"	1	0	2	1	1	1	0	1	0	3	4	4	3	8	7	1	5	3	5	6	7
"Hydrogen" + "sensors"	2	1	2	1	4	6	0	2	1	4	8	3	1	9	5	7	5	15	7	3	6
"Hydrogen" + "carbon monoxide"	2	2	2	0	3	3	6	5	8	4	6	10	7	16	10	4	1	2	8	4	4
"Hydrogen" + "metal hydride"	1	0	1	1	2	1	5	5	3	2	5	2	3	4	3	1	1	3	3	0	4
"Hydrogen" + "storage vessel"	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	2
"Hydrogen" + "shift reactor"	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	1
"Hydrogen" + "car"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0
"Hydrogen" + "electrochemical sensors"	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	1	0	0	0
"Hydrogen" + "ICE"	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0
"Hydrogen" + "ignition"	1	0	1	1	0	0	1	1	0	0	0	0	1	0	2	0	1	1	0	0	0
"Hydrogen" + "PEM"	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
"Hydrogen" + "poisoning"	0	0	1	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
"Hydrogen" + "powertrain"	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
"Hydrogen" + "pressure vessel"	2	0	4	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
"Hydrogen" + "spark ignition"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0
"Hydrogen"	190	212	242	244	236	216	247	238	267	301	300	336	351	334	314	249	325	295	304	265	411

No patents were found for the following keywords: "hydrogen" + "bipolar plate"; "hydrogen" + "ECU"; "hydrogen" + "electrolyser"; "hydrogen" + "pressure gauge".

Table 3
Number of citations of patents issued in a specific year (“hydrogen” + “ICE” in abstract)

Year for (“hydrogen” + “ICE” in abstract)	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
2000	0	0	0	0	0	0	0	0	3	4	7	1	7	5	14	30	18	20	27
2003	0	0	0	0	0	0	0	0	0	0	0	4	5	6	16	16	7	14	18
1999	0	0	0	0	0	0	0	3	2	8	9	7	5	4	17	34	11	12	14
1992	0	2	2	6	2	1	2	5	6	7	2	7	6	4	6	1	7	6	8
2002	0	0	0	0	0	0	0	0	0	0	2	6	9	7	5	10	3	10	8
1994	0	0	2	3	3	2	3	2	1	5	4	1	2	1	0	2	0	0	6
1998	0	0	0	0	0	0	1	2	5	3	2	10	5	1	1	3	2	4	6
2001	0	0	0	0	0	0	0	0	0	2	0	1	0	11	12	12	2	8	6
2004	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	4	2	2	6
1996	0	0	0	0	1	1	1	5	0	2	0	4	3	2	6	28	13	4	5
1991	0	1	0	1	0	2	5	3	2	1	1	1	4	2	3	11	12	22	3
1993	0	0	3	0	2	3	0	1	1	1	0	4	1	0	1	2	5	6	3
2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	3
2009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3
1995	0	0	0	0	0	0	1	0	2	0	1	2	5	4	3	2	1	1	2
1997	0	0	0	0	0	0	0	0	0	1	1	1	1	1	2	1	0	0	1
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6	2	4	1	1
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	4	1
1990	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Years where no citations have been included.

Table 4
Number of citations of patents issued in a specific year (“hydrogen” + “tank” in abstract)

Year for (“hydrogen” + “tank” in abstract)	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
1997	0	0	0	0	0	0	2	2	3	13	23	18	18	17	10	38	33	31	26	55
2000	0	0	0	0	0	0	0	0	0	3	6	7	6	11	8	10	14	31	37	52
2001	0	0	0	0	0	0	0	0	0	0	3	8	11	29	38	29	36	26	18	31
1998	0	0	0	0	0	0	0	2	1	3	5	7	9	14	11	17	17	11	19	24
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	24	27	28	34	24
2002	0	0	0	0	0	0	0	0	0	0	0	4	10	9	17	18	28	16	11	23
2003	0	0	0	0	0	0	0	0	0	0	0	0	5	10	18	15	31	23	20	21
2004	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	15	19	15	9	17
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	10	22	16
1999	0	0	0	0	0	0	0	0	1	10	18	16	36	27	22	7	21	16	8	15
2006	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	12	12	21	14
2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	10
1996	0	0	0	0	0	3	1	4	6	8	9	7	14	8	6	9	7	7	9	8
1993	0	0	2	1	4	8	5	5	3	7	5	2	6	12	7	16	15	6	10	7
1992	0	1	5	5	8	7	1	6	3	10	9	5	13	14	11	14	4	3	4	6
1994	0	0	0	1	1	0	0	1	4	5	6	6	2	3	4	6	7	2	8	3
1995	0	0	0	0	0	1	5	5	11	5	11	20	15	11	15	11	24	11	3	3
2009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
1991	0	1	2	2	5	1	2	2	3	1	3	3	1	2	4	4	4	2	0	1
2010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1990	1	3	2	0	0	2	1	2	0	1	1	3	5	2	2	1	1	3	4	0

The column of year 1990 has not been included because there are no citations for that year.

Table 5
Number of citations of patents issued in a specific year (“hydrogen” + “fuel cell” in title)

Year for (“hydrogen” + “fuel cell” in title)	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
2001	0	0	0	0	0	0	0	0	0	0	1	16	11	11	12	20	21	31	51
2000	0	0	0	0	0	0	0	0	0	5	0	10	11	6	17	26	19	31	41
2002	0	0	0	0	0	0	0	0	0	0	0	3	5	11	14	17	18	14	28
1999	0	0	0	0	0	0	0	0	0	2	1	8	8	6	12	7	13	17	27
1998	0	0	0	0	0	0	0	0	1	1	3	2	6	2	13	8	6	9	22
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	11	11	20
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	3	9	13	6	16	18
2004	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	3	6	8	13
2006	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	2	11
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
1992	2	2	1	1	0	0	0	0	0	1	1	2	3	4	6	3	2	2	6
1997	0	0	0	0	0	0	1	1	6	4	13	11	10	5	1	2	7	6	3
1993	0	2	0	3	1	1	2	0	2	6	2	1	0	2	5	4	3	4	2
1995	0	0	0	0	1	4	5	0	3	5	7	6	5	2	1	1	1	8	2
1994	0	0	0	0	0	1	2	3	6	5	12	8	9	4	4	1	5	1	1
2009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Years where there are no citations have not been included.

Table 6
Number of citations of patents issued in a specific year (“hydrogen” + “storage” in title)

Year for (“hydrogen” + “storage” in title)	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
2004	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	18	10	22	15	24
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	4	7	5	11	10	21	12	21
1990	1	6	6	8	18	11	23	11	12	12	17	11	11	3	9	4	9	2	6	5	17
2006	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	3	7	8	17
2007	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	6	16
2008	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	12
1999	0	0	0	0	0	0	0	0	0	3	6	28	12	13	15	8	8	12	5	2	11
2001	0	0	0	0	0	0	0	0	0	0	0	6	17	9	25	11	25	23	22	10	11
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	4	19	18	17	12	11
2000	0	0	0	0	0	0	0	0	0	0	1	18	15	14	19	4	28	20	13	9	9
1996	0	0	0	0	0	0	1	12	21	24	18	21	16	10	21	8	12	14	17	6	8
1998	0	0	0	0	0	0	0	0	1	4	5	13	14	16	13	7	11	12	8	6	8
1997	0	0	0	0	0	0	0	1	3	9	9	6	5	2	12	5	14	23	18	9	7
2005	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	4	10	7
2010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
1994	0	0	0	0	0	5	10	8	9	5	7	11	5	6	1	3	6	7	3	1	2
1995	0	0	0	0	0	0	7	7	8	11	14	8	5	12	1	1	2	10	3	1	2
1991	0	0	1	2	9	6	9	5	8	3	1	0	2	2	3	1	0	1	1	0	1
1992	0	0	0	3	15	17	25	10	10	5	5	4	4	4	2	3	1	3	3	1	1
2009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1993	0	0	0	0	3	1	14	1	4	1	3	0	1	2	1	1	0	1	0	0	0

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