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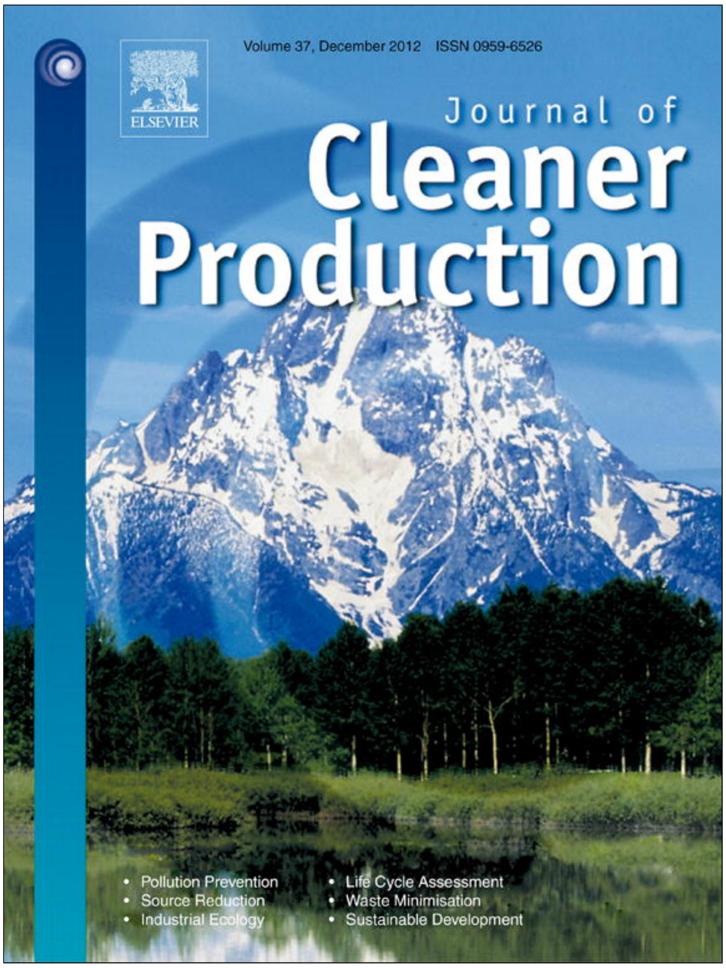


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Journal of Cleaner Production 37 (2012) 211–220

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Technological diversity of emerging eco-innovations: a case study of the automobile industry

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ARTICLE INFO

*Article history:*
Received 20 February 2012
Received in revised form
5 July 2012
Accepted 6 July 2012
Available online 24 July 2012

*Keywords:*
Eco-innovation
Prototype analysis
Technological diversity
Era of ferment

ABSTRACT

The automobile industry is in a remarkable state as not one, but multiple alternative fuel powertrain technologies are challenging the gasoline/diesel fueled internal combustion engine (ICE). This indicates a high level of uncertainty and suggests that the automobile industry might be transitioning past the ICE powertrain as the dominant design. Our research analyzed the technological diversity of alternative fuel vehicles (AFVs) from 1991 to 2011. We collected an unique database of 884 AFVs from the 15 largest auto manufacturers. This data was analyzed on a firm, technological, and industrial level. Results showed an increase in technological diversity over the study period. Although electric vehicles are the technology du jour, auto manufacturers are continuing to develop a variety of AFVs. This indicates that incumbent firms do not know if/which powertrain design will emerge as the dominant technology. Indeed, high heterogeneity in vehicle demand through influences such as government policies could lead to several different types of AFVs competing in distinct markets. In addition to analyzing industrial dynamics in the automobile industry, we also provided policy recommendations for how governments can support the transition toward more sustainable automobile transportation.

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## 1. Introduction

Due to factors such as government regulation of emissions, advances in technology, and increases in oil prices, the automobile market has entered into a period of flux and uncertainty. Vehicle manufacturers have reacted by developing several powertrain alternatives to the internal combustion engine (ICE)[1]. The variety of powertrain technologies available for purchase or in advanced stages of development is as diverse as it has been since the ICE became the dominant design for automobiles in the early 1900s. The actions of incumbent car makers regarding alternative fuel powertrain innovations during this period are likely to play an important role in determining the future of automobile technology.

Since 1990, there has been a great deal of activity regarding the development of alternative fuel vehicles (AFVs[2]) specifically through government policies and technological developments. This had led to a situation where AFVs are becoming more competitive with ICE vehicles (IEA, 2009). Government policies that have encouraged the development and commercialization of AFVs include California's Zero Emission Vehicle (ZEV) mandate in 1990, the 2005 US Energy Policy Act, and the 2009 EU emissions regulation (Bedsworth and Taylor, 2007; CBO, 2010; European Commission, 2009). As a case in point, the ZEV mandate led to a large number of Electric Vehicle (EV) prototype and production models in the 1990s. Low sales and a repeal of the regulation, under industry pressure, encouraged firms to shift focus to other alternative fuel powertrains such as hybrid-electric (Dijk and Yarime, 2010). As technologies have improved, niche markets have opened up where AFVs have a competitive advantage over ICE vehicles (Van Bree et al., 2010). Oltra and Saint Jean (2009) showed that incumbents have increased the proportion of alternative fuel technologies such as electric, hybrid-electric, and hydrogen vehicles in their R&D efforts. Recent market introductions also indicate that large auto makers now view the EV market as a commercial opportunity instead of a regulatory requirement (Magnusson and Berggren, 2011).

With this paper we aim to address both an empirical gap in the literature on the automotive industry and a gap with regard to innovation theory. The empirical gap relates to the fact that existing

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[1] For purposes of this research, we will refer to an internal combustion engine that uses either diesel or gasoline as an ICE. Other types of fuels used in an ICE e.g., hydrogen will be so identified.

[2] We use AFVs to designate vehicles that have powertrain technologies radically different from the conventional ICE or use a fuel other than gasoline/diesel e.g., hydrogen, electricity, flex-fuel, compressed natural gas, and liquid petroleum gas.

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industry-wide analyses of firm development of AFV technologies use patent data. We offer a new perspective by analyzing production and prototype models that have been developed by incumbent firms. The gap in innovation theory relates to technological change involving eco-innovations. Eco-innovations distinguish themselves from other innovations in that they specifically provide a lower environmental impact than the conventional technology (Rennings, 2000). Because of this, governments have used policies to help make eco-innovations competitive in the market (Jaffe et al., 2005). While there is a wealth of literature studying technological change involving "normal" innovations, industrial dynamics involving eco-innovations remain somewhat of a mystery. We help to address this gap by analyzing the technological diversity of alternative fuel vehicles during an era of ferment (a period of uncertainty, expansion of technological diversity, and a high firm entry rate).

The research question to this paper is, *what are the actions of incumbent automobile firms with regard to the multiple alternative fuel powertrain technologies that are competing among each other and with the internal combustion engine*? Answering this research question entails addressing three research sub-questions, respectively on the industry, technology, and firm level. (1) What AFV technologies has the automobile industry developed since 1991? (2) What production dynamics have the different AFV technologies displayed? (3) What are the actions of individual firms regarding the production of AFV models? The primary goal of our research is to analyze technological diversity of eco-innovations during an era of ferment. A secondary goal is to use that analysis to recommend policies to support the development and adoption of eco-innovations.

This paper is organized as follows. Following this introductory chapter is a section (Section 2) that reviews foundational theoretical elements used in our article (technological transitions, incumbents, and eco-innovations). Section 3 briefly identifies the different types of AFV technologies that will be studied in this research, policies that have influenced their development, and vehicle sales statistics. The method used in this research was a collection and analysis of production and prototype AFV models developed by incumbent automobile firms and is further described in Section 4. Section 5 presents and discusses the results of this analysis from an industry, technology, and firm level. Lastly, Section 6 provides concluding statements that highlight the main points of this research along with policy recommendations.

## 2. Theory

### 2.1. Technological diversity in technology transitions

Researchers have used industrial dynamics such as firm entry rate and level of technological diversity to indicate technological transitions (Klepper, 1996; Van Dijk, 2000). Perhaps the most well known technological transitions theory is the product life cycle (PLC) which describes the following cyclical process: radical innovation → era of ferment → dominant design → era of incremental improvement → radical innovation → era of ferment etc. (Abernathy and Utterback, 1978; Tushman and Anderson, 1986). Eras of ferment are marked by increases in technological diversity while eras of incremental improvements are characterized by a single dominant technological design (Klepper, 1996). Not all technological transitions follow the PLC, however, with studies showing that a dominant design may not emerge from an era of ferment. Instead several different technologies can be successful in different markets (Teece, 1986; Windrum and Birchenhall, 1998). Exceptions to the PLC are often marked by high levels of demand heterogeneity within an industry (Bonaccorsi and Giuri, 2000).

### 2.2. Incumbents and technological transitions

The literature is somewhat ambiguous as to whether incumbent or startup firms are more likely to develop radical innovations (Foster, 1986; Chandy and Tellis, 2000). A broad examination of historical technological transitions shows that incumbent firms can and do develop radical innovations (Chandy and Tellis, 2000; Hill and Rothaermel, 2003). Specifically within the automobile industry there can be no doubt that incumbent manufacturers have been in the vanguard in developing radical innovations in the form of AFVs e.g., the GM EV1, Toyota Prius, Nissan Leaf, and Honda FCX Clarity. Firms pursue radical innovations because they offer the possibility of increased competitive advantages. However, the literature stresses that even during technological transitions incumbents are beholden to a customer base that uses the conventional technology (Christensen, 1997). This encourages incumbents to develop innovations that enhance the existing technology. Therefore, incumbent firms have often simultaneously pursued both incremental improvements to the dominant design as well as radical new innovations (Jiang et al., 2010).

### 2.3. Eco-innovations and technological transitions

Eco-innovations compete in the market with all other products and services. In that regard, a technological transition involving an eco-innovation experiences the same fundamental industrial dynamics as would any other innovation. However, eco-innovations fundamentally differ from other new technologies in that they necessarily provide a reduced environmental impact when compared to the dominant design (Rennings, 2000). Additionally, the environmental benefits of eco-innovations are not exclusive to the owner, so society as a whole reaps rewards from their use. Furthermore, externalities (knowledge spillover and reduction in pollution) inherent in eco-innovations cause the market to disincentivize their development. For those reasons, governments have used policies to support the development and adoption of eco-innovations (Rennings, 2000; Jaffe et al., 2005). Environmental policies to induce technological change are usually described as being technology forcing or market based (Jaffe et al., 2002). Technology forcing policies set targets for products e.g., lower pollution, inducing firms to develop innovations in order to meet the goals. This approach has been shown to be successful in reducing vehicle emissions in the US automotive sector (Lee et al., 2010). Market based policies such as subsidies and pollution taxes encourage firms to innovate in order to be more competitive in the market. Such policies have been influential in establishing a market for flex-fuel vehicles in the US (CBO, 2010).

## 3. Alternative fuel vehicles and related policies

Some background information on the competitive environment of automobiles is useful in order to understand a thorough analysis of incumbent actions regarding AFV development. This section details how AFV powertrain technologies differ from one another relative to the ICE powertrain. It also identifies technologies, policy frameworks, and sales figures as they relate to AFVs.

### 3.1. Alternative fuel vehicles

One of the fundamental elements of a technological transition is how an innovation compares to the conventional technology. In this way, innovations are often understood to be incremental if they reinforce existing technology or radical if they require new expertise or knowledge (Tushman and Anderson, 1986). Henderson and Clark (1990) expanded on this theoretical framework by

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describing innovations based on their relation to core components and linkages between those components. Hekkert et al. (2005) modified the Henderson and Clark framework to place innovations in a broader socio-economic context. This was accomplished by replacing 'changes in linkages between core components' (in the Henderson and Clark framework) with 'changes to socio-economic environment'. Fig. 1 uses the framework from Hekkert et al. (2005) to provide a graphical representation analyzing innovations relative to the ICE powertrain and the socio-economic environment (fueling infrastructure). Within the socio-economic environment, innovations can be confined to the product architecture (artifactual) or can influence the wider socio-economic system (systemic).

In Fig. 1, turbocharging is incremental and artifactual because it represents an innovation using both the ICE powertrain and existing fueling infrastructure (Berggren and Magnusson, 2012). A flex-fuel vehicle is an incremental innovation in that it represents a small change to the ICE powertrain, but also a systemic innovation because it can use the ethanol-gasoline mixture flex-fuel (Yu et al., 2010). A Hybrid-Electric Vehicle (HEV) is a radical and artifactual innovation because it represents fairly dramatic changes to the ICE powertrain (batteries and an electric motor) but no significant changes to fuel infrastructure. The plug-in HEV powertrain, however, does require new fueling infrastructure (charging stations), so it also includes systemic changes to the socio-economic environment. EV and Hydrogen Fuel Cell Electric Vehicles (FCEV) are radical and systemic innovations because both the ICE powertrain and fueling infrastructure change dramatically (Pohl and Elmquist, 2010; Van den Hoed, 2006). Hydrogen ICE ($H_2$ ICE) vehicles, Liquid Petroleum Gas (LPG) vehicles, and Compressed Natural Gas (CNG) vehicles are artifactual and systemic innovations, because the ICE powertrain does not change significantly but they do require new fuel infrastructure.

An important distinction needs to be made between HEV/Plug-in HEV and EV/FCEV. All four types of AFVs represent radical changes to the ICE powertrain. However HEVs/Plug-in HEVs still use the ICE in addition to batteries and an electric motor. In that way, both HEVs and Plug-in HEVs can be seen as reinforcing the existing dominant ICE design (they are competence-enhancing innovations). This differs from EV and FCEV which are competence-destroying innovations and require incumbent auto manufacturers to develop completely new expertise. Dominant designs emerging from competence-enhancing technologies are more likely to come from incumbent as opposed to startup firms (Anderson and Tushman, 1990).

### 3.2. Alternative fuel vehicles in our study

The alternative fuel vehicles included in our research predominantly differ from the dominant ICE design in terms of their

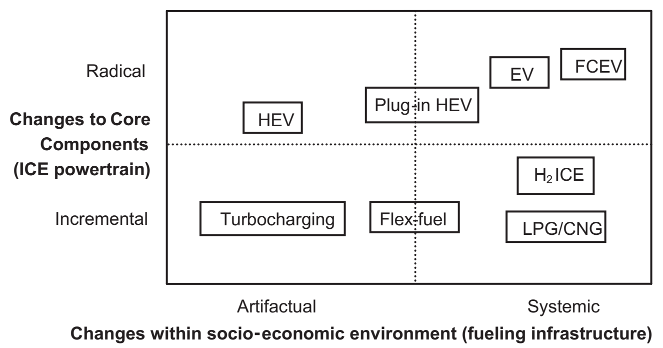


**Fig. 1.** Powertrain innovations relative to the ICE powertrain and fueling infrastructure (based on figures from Henderson and Clark, 1990 and Hekkert et al., 2005).

powertrain architecture or the fuel that they use. Table 1 shows the AFVs included in our study: flex-fuel, LPG, CNG, $H_2$ ICE, HEV, EV, and FCEV. Table 1 below outlines these innovations in terms of the fuels that they use, barriers that limit their adoption, and their advantages relative to the ICE powertrain.

Table 1 shows that the alternative fuel powertrains in our study offer lower vehicle emissions ($CO_2$ and toxic substances)[3] and fuel costs, but face barriers of high purchase costs and a lack of fuel infrastructure. Due to those barriers as well as externalities identified in the theory section, governments have used policies to help support the development and adoption of AFVs. A description of such policies is provided below.

### 3.3. Government policies regarding alternative fuel vehicles

AFVs as eco-innovations have a lower environmental impact than the dominant technology (ICE vehicles). In addition to technology forcing and market based policies identified in the theory section, there are also several additional policy approaches that are relevant for transportation. Table 2[4] provides examples of different policy approaches that governments have used to support AFVs: demand-side (financial and marketing), supply-side (regulation and financial), infrastructure, land use planning, pilot projects, and public transport (adapted from Blok and Van Wee, 1994). These policies attempt to encourage AFV development and adoption in different ways. Supply and demand policies target market dynamics while infrastructure and land use policies influence the physical environment in which the market functions. Pilot projects attempt to identify market viability and public transport policies determine how governments provide transportation to their citizens. Of particular interest for AFVs are policies that seek to shift consumer attitudes about cost from purchase price to total cost of ownership. Studies show that consumers tend to devalue a delayed outcome even if it is comparatively greater than the immediate outcome (Brown, 2001). Compared to ICE vehicles, almost all AFVs have a higher purchase cost but lower operating costs. In some situations that could lead to lower lifetime vehicle costs. For this reason, governments and firms are educating consumers about total cost of ownership in hopes of increasing AFV adoption.

In addition to the different approaches identified in Table 2, AFV policies can also be categorized as being technology specific or economy wide (Sandén and Azar, 2005). With technology specific policies, governments target the innovations that they wish to support. With economy wide policies, governments identify a particular goal e.g., reduced environmental impact, while not indicating which innovations need to be used to achieve that target.

The 2005 US Energy Policy Act is an example of a successful technology specific policy that contributed to the establishment of a significant market for both flex-fuel vehicles (~7.7% of US vehicle sales since 2005) and HEVs (~2.5% of US vehicle sales since 2005) (US DoE, 2011a). The ZEV mandate, however, was not successful in forcing the development and adoption of zero-emissions vehicles largely because auto manufacturers deemed the requirements to be too onerous and challenged it in court (Bedsworth and Taylor, 2007). The ARPA-E policy has provided low-interest loans to companies developing eco-innovations. Some of those companies have been successful (Tesla) and others less so (Solyndra).

[3] It is worth noting that emissions levels for vehicles that use electricity (HEV, Plug-in HEV, and EV) are dependent on the source of that electricity. As such, $CO_2$ emissions from an EV that is powered by electricity from coal plants will be higher than the same EV that uses emissions from renewable sources.

[4] This list of policies is by no means meant to be exhaustive or the most successful policies, but rather illustrative in the ways that governments support AFVs.

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**Table 1**
Fuels, barriers, and advantages of alternative fuel powertrains (Yu et al., 2010; US DoE, 2011a; US DoE, 2011b; Bedsworth and Taylor, 2007; Bakker, 2010).

| | Fuel | Barriers | Advantages to ICE powertrain |
|---|---|---|---|
| Flex-fuel | Gasoline or E85 | Lack of flex-fuel infrastructure | Lower emissions, decreased reliance on oil |
| LPG | LPG | Lack of LPG infrastructure | Lower emissions, lower fuel costs |
| CNG | CNG | Lack of CNG infrastructure | Lower emissions, lower fuel costs |
| $H_2$ ICE | Hydrogen | Higher purchase cost, lower driving range, lack of hydrogen infrastructure | Decreased reliance on oil |
| HEV | Gasoline/diesel | Higher purchase cost | Lower emissions, lower fuel costs |
| Plug-in HEV | Gasoline/diesel or electricity | Higher purchase cost, lack of recharging infrastructure | Lower emissions, lower fuel costs |
| EV | Electricity | Higher purchase cost, long charge time, lower driving range, lack of recharging infrastructure | Lower emissions, lower fuel costs |
| FCEV | Hydrogen | Higher purchase cost, reliability concerns, lack of infrastructure | Lower emissions, potentially low fuel costs |

Technology specific policies are often used to provide support for radical innovations that may not be able to compete under normal market conditions. Once the innovation has matured (the notion goes), then supporting policies will no longer be necessary (Kemp, 1997). This method was used in the US as supporting policies recently expired for flex-fuel vehicles in 2011 and HEVs in 2010.

EU emissions regulation and the French bonus/malus policy are examples of economy wide approaches that have helped to lower vehicle emissions (Wards Auto, 2011). CAFE regulation has directed manufacturers to develop automobiles with higher fuel efficiency. All three policies have successfully supported more environmentally friendly vehicle technologies. However, they have not necessarily encouraged the development or adoption of specific AFVs. This is because environmental impacts are the important element for economy wide policies. It is irrelevant whether those reduced environmental impacts come from AFVs or incremental eco-innovations to the ICE. In general, economy wide policies, especially those that set environmental standards, have been effective in promoting incremental innovations. Technology specific policies have been more effective in stimulating the development and adoption of radical eco-innovations (Kemp, 1997).

**Table 2**
Transportation policies (French Embassy, 2011; Elektrisch Vervoer Centrum, 2012; European Commission, 2009; Bedsworth and Taylor, 2007; CBO, 2010; US DoE, 2010).

| Policy approach | Specific type | Example | Measure |
|---|---|---|---|
| Demand-side | Financial | 2005 US Energy Policy Act | Tax credits to HEV buyers |
| | | France bonus-malus | Subsidy/tax on vehicle efficiency |
| | Marketing | Elektrisch Vervoer Centrum | Informs potential EV customers |
| Supply-side | Regulation | ZEV mandate | Number of zero-emissions vehicles |
| | | EU emissions | Vehicle emissions |
| | | CAFE | Fuel efficiency |
| | Financial | 2005 US Energy Policy Act | Tax credits to ethanol producers |
| | | ARPA-E | Low-interest loans to AFV companies |
| Infrastructure | | Amsterdam Elektrisch | Refueling stations |
| Land use | | Amsterdam Elektrisch | Free parking in Amsterdam for EVs |
| Pilot projects | | HyFleet | FCEV demonstration project |
| Public transport | | NY fleet | HEV buses in municipal fleet |

### 3.4. Alternative fuel vehicle sales

As identified in Fig. 1, alternative fuel vehicles represent eco-innovations to the ICE powertrain and fueling infrastructure. The section above provided some basic information about the technological make-up of those different innovations, but that does not give an indication of how AFVs have been received in the market. It is important to note that not all AFV technologies are at the same level of commercialization. Table 3[5] supplies the number of AFVs that were sold, leased, or converted in the US from 2000 to 2009. Table 4 gives AFV production statistics for Japan from 2000 to 2009. Trends in Table 3 include an increase in the number of HEVs, a decrease in the number of CNG and LPG vehicles, and an increase followed by a decrease in the number of EVs. Flex-fuel vehicles constituted the largest portion of AFVs with 7% of all automobiles in 2009 followed by HEVs at 3% in 2009. The other AFV technologies comprised a very small proportion of total vehicle sales, leases, or conversions in the US.

Table 4 provides a different picture of a country's production approach to AFVs. Notably, Japan is not a producer of flex-fuel vehicles. HEVs have been the most popular form of AFV in Japan with production reaching 5.4% of all automobiles in 2009. Other types of AFVs have had limited production numbers with CNG and LPG vehicles increasing and decreasing during the 2000s. EVs and hydrogen vehicles had very small production numbers. However, the number of EVs produced increased from 0 in 2008 to 1706 in 2009, which could indicate a growing interest in the technology. It should be noted that the sales Figures in Tables 3 and 4 include more firms than our own analysis and may include niche market vehicles that incumbents typically do not produce. Therefore the statistics in Tables 3 and 4 may not completely correlate with the AFV production data provided later in this research. However, the data do show that AFV technologies are in different stages of commercialization and identify that they can be competitive with ICE vehicles e.g., flex-fuel vehicles and HEVs.

## 4. Methods

Our research analyzed technological diversity of AFV powertrains as developed by incumbent firms. Other technologies such as new materials (carbon fiber) have also been used to increase vehicle fuel efficiency, but our research chose to focus on

[5] Tables 3 and 4 represent the data that were available to the authors. Unfortunately the data were not available for the entire study period of our analysis nor was it possible for harmonization of the two data sets.

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**Table 3**
Vehicles sold, leased, or converted in the US from 2000 to 2009 by powertrain type (US DoE, 2011c).

| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|
| All Vehicles | 15,869,103 | 14,646,211 | 15,066,949 | 14,753,910 | 15,011,888 | 14,966,290 | 14,263,685 | 13,819,125 | 11,136,230 | 10,429,553 |
| CNG | 9501 | 11,121 | 8988 | 6122 | 7752 | 3304 | 3128 | 2487 | 4440 | 3770 |
| EV | 6215 | 6682 | 15,484 | 12,395 | 2200 | 2281 | 2715 | 3152 | 2802 | 2255 |
| Flex-fuel | 600,832 | 581,774 | 834,976 | 859,261 | 674,678 | 743,948 | 1,011,399 | 1,115,069 | 1,175,345 | 805,777 |
| HEV | 9350 | 20,282 | 36,035 | 47,600 | 84,199 | 209,711 | 252,636 | 352,274 | 312,386 | 290,271 |
| Hydrogen | 0 | 0 | 2 | 6 | 31 | 74 | 40 | 63 | 63 | 26 |
| LPG | 4435 | 3201 | 1667 | 2111 | 2150 | 700 | 473 | 356 | 695 | 126 |

**Table 4**
Vehicles produced in Japan from 2000 to 2009 by powertrain type (JAMA, 2011).

| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|---|---|
| All Vehicles | 10,886,330 | 10,559,612 | 11,110,702 | 11,112,357 | 11,366,999 | 11,662,267 | 12,382,813 | 12,573,302 | 12,152,115 | 8,687,791 |
| CNG | 2447 | 4028 | 3972 | 3852 | 3265 | 3066 | 3091 | 2175 | 2379 | 1197 |
| EV | 150 | 183 | 83 | 49 | 17 | 0 | 0 | 0 | 0 | 1706 |
| HEV | 12,950 | 25,089 | 15,514 | 42,423 | 66,540 | 61,263 | 90,410 | 90,523 | 121,101 | 466,631 |
| Hydrogen | 0 | 0 | 0 | 0 | 0 | 2 | 5 | 1 | 0 | 5 |
| LPG | 2183 | 3157 | 2194 | 3244 | 3121 | 1799 | 2438 | 874 | 609 | 450 |

powertrains. Specifically, we looked at how AFV powertrains have been developed from an industry, technology, and firm level. As Tables 3 and 4 describe, the number of AFVs that have been produced and purchased varies widely by technology. In order to examine AFV technological variety, we have opted to do an analysis of prototype and production models instead of focusing only on vehicle sales. This allows for a better comparison of how incumbents have approached the development of AFV technologies that are in vastly different stages of commercialization e.g., flex-fuel (functioning markets) and hydrogen vehicles (pre-commercialization), than by merely looking at sales figures.

A prototype and production model analysis is useful for gaining insights into industries in situations where there are low sales and a large variety of developing alternatives; such as that found in emerging technologies (Suarez, 2004; Bakker et al., 2012; Sierzchula et al., 2012). The number of prototype or production models developed by auto manufacturers can be used to determine their level of interest regarding a particular alternative fuel powertrain. This allows for comparison between competing technologies and is appropriate for examining the current incumbent development efforts regarding AFVs. However, it is important to point out that our data is limited to car models that are presented to the public. As auto shows have traditionally been used for presenting and legitimizing new vehicles and technologies, we assume that in general manufacturers display their AFV development at such venues. Any AFV R&D not made public would not be included in this analysis.

We collected information about prototype and production models from the 15 largest incumbent car makers according to the 2009 production figures from the International Organization of Motor Vehicle Manufacturers (OICA, 2010). These companies accounted for 83% of vehicle sales in 2009 and include: Toyota, General Motors, Volkswagen, Ford, Hyundai, PSA, Nissan, Fiat, Suzuki, Honda, Renault, Daimler, Chana Automobile, BMW, and Mazda. Only vehicles that were developed by these incumbents were analyzed. Conversion of an incumbent model from using gasoline or diesel to an alternative fuel by a 3rd party company was not included in the vehicle database. A study period of 1991–2011 was used for this research because 1991 captures the influence of California's ZEV mandate on AFV development. We gathered information about 884 production and prototype AFV models that used any of five different alternative fuels (electricity, compressed natural gas, liquefied petroleum gas, hydrogen, or flex-fuel). This created five categories of AFV vehicles according to fuel type plus a sixth in HEV[6] where gasoline/diesel and electricity both power the automobile. In addition to AFVs that employed one fuel type, there were also examples of models that used two or three different alternative fuels. These are referred to as multi-fuel vehicles and are analyzed as a group in the results section.

We searched both annual reports and company press releases to identify the AFV models in this study. We used the following combination of search terms (1) fuels: "flex-fuel" OR "compressed natural gas" OR "liquid petroleum gas" OR "Hybrid" OR "electric vehicle" OR "hydrogen" and (2) model type "concept" OR "prototype" OR "production". Data for the following characteristics were collected for each model: manufacturer, model, fuel type, classification (prototype or production), and introduction date. In the case of a prototype the introduction date was when it is presented to the public (usually at an auto show) and for a production vehicle it was the date that it was available for purchase. If a vehicle had two models with different battery types, e.g. Nickel Metal Hydride (NiMH) and Lithium-ion, then it was counted as two models. Instances of additional generations of AFVs were also included in the data set. For example, the Toyota Prius appeared as a prototype in the 1995 Tokyo Motor Show (Tokyo Motor Show, 2011) and has been available for purchase since 1997 (Toyota, 2011). In the situation where a vehicle had a prototype and production model, both were included in the database. This approach provides a more accurate representation of when auto manufacturers are developing AFV technologies. There have been three generations of the Prius that use NiMH batteries and a plug-in prototype that uses lithium-ion batteries appeared in 2009. The Toyota Prius had five vehicles in the database (one for the prototype that used NiMH, one for each of the three production generations with NiMH, and one for the prototype that used lithium-ion batteries). For companies such as GM that rebrand the same vehicle under different subsidiaries e.g. GMC Sierra and Chevrolet Silverado, only one model was included in the final data set. An important note is that partnerships did lead to similar vehicles among the studied firms e.g., PSA with the iON/C-Zero and Mitsubishi with the iMiEV.

[6] This research defines a hybrid-electric vehicle (HEV) as using both diesel/gasoline and electricity to power the wheels. "Micro-hybrid" systems like the PSA's e-HDi or GM's BAS system (start-stop and regenerative braking) do not meet this requirement and models using those systems were not included in the database.

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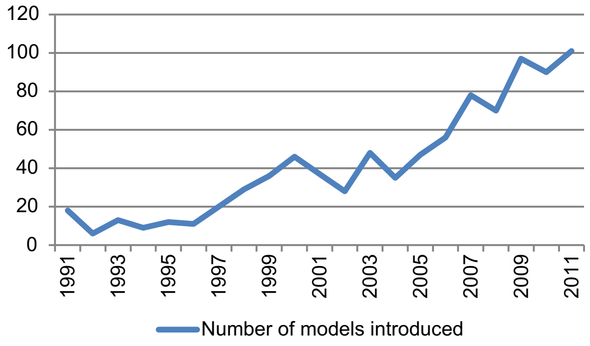


**Fig. 2.** Number of AFV models introduced.

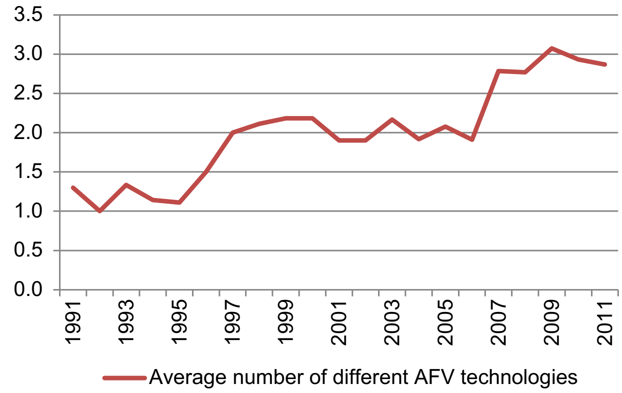


**Fig. 4.** Average number of different AFV technologies presented by manufacturers in a given year.

However, each of the companies in our study was independently run and thus was able to make its own decisions regarding alternative fuel technology development. For that reason, similar vehicles in two *different* companies were counted as two models in our database while similar vehicles within the *same* company (but under different subsidiaries) were counted as one model.

Different analyses of the prototype and production model database allow for viewing the development of AFVs from an industry, technology, and firm level. The industry level involves aggregating firm data in order to determine results such as the number of AFVs that have been developed during the study period and the breakdown of models according to prototype or production status. The technology level provides a yearly representation of the number of AFV models and manufacturers for each of the different powertrain types. The firm level presents the number of AFVs and type of powertrain technologies that each of the 15 firms developed.

## 5. Results

### 5.1. Industry level

Figs. 2–4 give an overview of AFV development from an industrial level including number of models introduced, number of firms introducing a model, and the average number of AFV technologies developed by manufacturers. Fig. 2 shows that the number of AFV models introduced in a given year fluctuated over the study period, but the general trend was an increase in this number. Fig. 3 shows that as a whole, the number of companies producing AFV models increased over the study period. For the final three years of the study (2009–2011), all incumbents presented an AFV model. Fig. 4 shows that the average number of AFV technologies developed by manufacturers increased over the study period from 1.3 to 2.9. As such, incumbents were more likely to present models with more diverse alternative fuel powertrains in 2011 than in 1991. Figs. 2–4 indicate that incumbents are uncertain about which technology will be successful, but they are also becoming more aggressive in their AFV development strategies. A larger number of incumbent auto manufacturers are developing more AFV models with a greater variety of powertrain technologies.

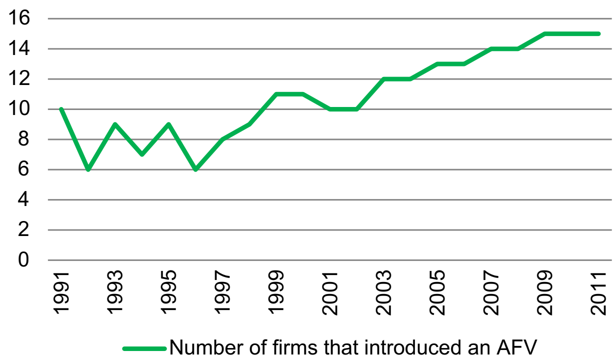


**Fig. 3.** Number of firms that introduced an AFV model.

Table 5 breaks down the models according to prototype or production status. This table shows that there were more prototype models (507) than production models (377) among the vehicles studied. Models that used incremental and systemic powertrain innovations (LPG, CNG and flex-fuel) were much more likely to have a high proportion of production vehicles than models that used artifactual and radical powertrain innovations (hydrogen, HEV, and EV). HEVs and EVs have seen the most balanced development of production and prototype vehicles. Production models accounted for 30% of all HEV models and 25% of all EV models. Models using incremental, systemic, artifactual and radical innovations appeared in the same year throughout the study period. This indicates that auto manufacturers as a whole are incorporating multiple types of innovations in AFV development strategies.

### 5.2. Technology level

Figs. 5 and 6 present the three year average of the number of prototype and production models that were presented for each AFV technology. Those figures complement Table 5 by showing the temporal relationship between the introduction of prototype and production models. AFVs that represented incremental innovations to the ICE powertrain (CNG, flex-fuel, and LPG) did not have many prototypes before the appearance of production models that used those technologies. Radical innovations to the ICE powertrain (HEVs and EVs) did show increases in prototypes before increases

**Table 5**
AFVs prototype or production status.

| | Prototype | Production | Total |
|---|---|---|---|
| Electricity | 97 (19%) | 33 (9%) | 130 (15%) |
| Hydrogen | 157 (31%) | 2 (1%) | 159 (18%) |
| Hybrid | 196 (39%) | 85 (23%) | 281 (32%) |
| CNG | 20 (4%) | 108 (29%) | 128 (14%) |
| LPG | 5 (1%) | 36 (10%) | 41 (5%) |
| Flex-fuel | 11 (2%) | 109 (29%) | 120 (14%) |
| Multi-fuel | 21 (4%) | 4 (1%) | 25 (3%) |
| | 507 (100%) | 377 (100%) | 884 (100%) |

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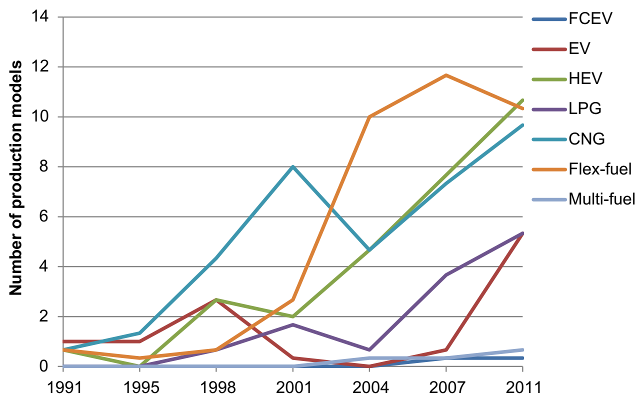


**Fig. 5.** Moving 3 year average of AFV production models from 1991 to 2011.

in production models. For HEVs this trend occurred over the entire study period, while for EVs it occurred after 2007. Hydrogen vehicles on the other hand, showed an increase followed by a decrease in the number of prototypes that were presented and had almost no production models during the study period. This indicates that HEVs and EVs experienced different industrial dynamics than did hydrogen models.

Similar to hydrogen vehicles with prototypes, flex-fuel vehicles displayed a boom and bust trend in the number of production vehicles that were introduced. However the two technologies may have experienced different industrial dynamics because they were in separate phases of commercialization. Table 3 showed that flex-fuel vehicles have an established market as opposed to hydrogen vehicles which are still in the pre-adoption phase of commercialization. Figs. 5 and 6 show that for radical AFVs, auto manufacturers developed prototypes before production models. However prototypes did not necessarily indicate that production models were going to be produced as shown by the hydrogen vehicle example. For incremental AFVs, auto manufacturers progressed directly to production models e.g., CNG, LPG, and flex-fuel vehicles.

It is important to note that Figs. 5 and 6 provide a generalization of AFV trends. The annual data often shows a more nuanced pattern. For example, flex-fuel vehicles had a much more dramatic rise and fall than is indicated in this graph. Detailed descriptions of AFV trends are available in Figs. 7–12.

Figs. 7–12 show the number of manufacturers and models with AFV technologies that were introduced from 1991 to 2011. Even though Fig. 2 shows that the annual number of AFV models introduced has increased, Figs. 7–12 indicate that this was not the case for all technologies. The development of CNG, HEV, and LPG

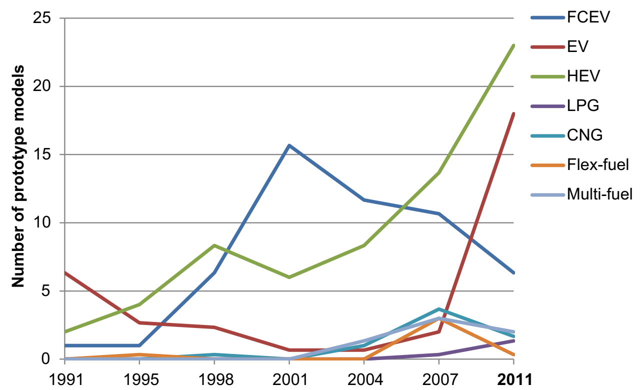


**Fig. 6.** Moving 3 year average of AFV prototype models from 1991 to 2011.

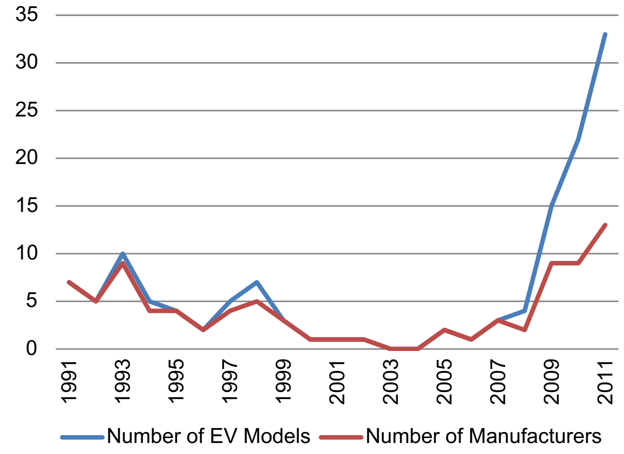


**Fig. 7.** Electric vehicle models.

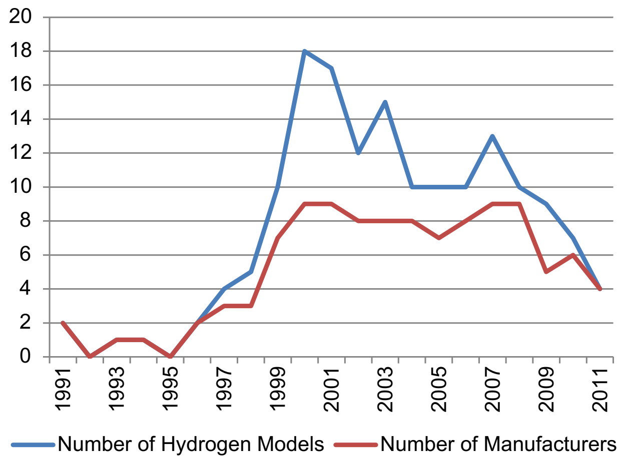


**Fig. 8.** Hydrogen vehicle models.

vehicles was sporadic throughout the study period with sudden increases followed by sharp declines in the number of models that were presented. For example, the dramatic increase in LPG vehicles in 2009 was due to Fiat making LPG alternatives for a large portion of its vehicle lineup. However as a whole, the number of models using those technologies displayed a general increase during the

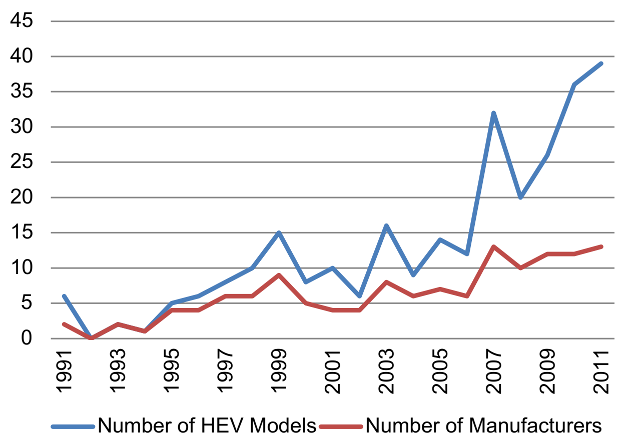


**Fig. 9.** Hybrid-electric vehicle models.

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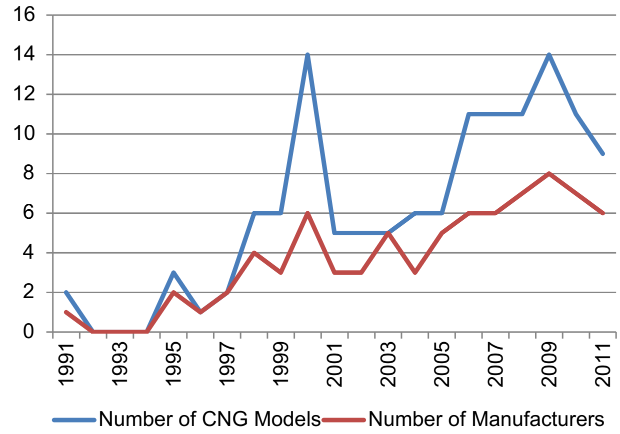


**Fig. 10.** CNG vehicle models.

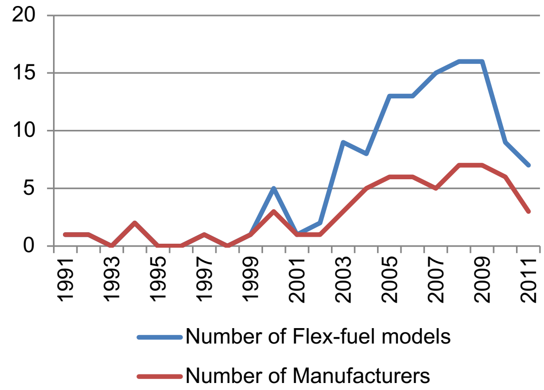


**Fig. 12.** Flex-fuel vehicle models.

study period. Flex-fuel vehicles, hydrogen vehicles, and EVs displayed a different path of development. Flex-fuel and hydrogen vehicles exhibited a large increase in the number of models over several years followed by a decline over many years. The number of EV models decreased from 1991 until 2000 followed by a period where very few models were presented. However, there was a dramatic increase at the end of the study period from three EV models in 2008 to 26 models in 2011. These results indicate that AFV technologies go in and out of style, which is consistent with the Bakker's (2010) findings regarding hydrogen vehicles and hype cycles.

In addition to the annual number of AFV models, Figs. 7–12 also show how many manufacturers presented those models. Within the individual AFV technologies, there appear to be two different periods of development regarding the number of manufacturers and the number of models. The first period of development is evident in Fig. 12 (flex-fuel vehicles) from 1991 to 2011, Fig. 7 (EVs) from 1999 to 2007, and Fig. 8 (hydrogen vehicles) from 1991 to 1996. This period represents a situation where manufacturers are only making one model with a specific AFV technology. In the other period of development, e.g. flex-fuel vehicles from 2003 to 2008 or HEVs from 2007 to 2011 manufacturers make multiple models with that technology. These two periods of development coincide with the boom and bust cycles which have characterized particular AFV technologies and provide a useful way of gauging manufacturer actions.

### 5.3. Firm level

Fig. 13 provides the number and type of AFV models that have been presented by individual firms. This figure shows that incumbents have been developing a variety of models with different AFV powertrains throughout the study period. The efforts of some companies have been targeted toward specific technologies such as Toyota with HEVs, Nissan with EVs, and Fiat with CNG vehicles. Other companies such as Mazda, Ford, and Volkswagen have been fairly balanced regarding the development of models with different AFV technologies. In general, the firms that produced the most vehicles (based on 2009 OICA production statistics) also developed the largest number of AFV models. Toyota, Volkswagen, Ford, and General Motors were the four largest auto manufacturers by vehicle production and represent four of the five manufacturers that made the most AFV models. Mazda, Chana, and BMW produced the fewest vehicles among the surveyed firms and also presented the fewest AFV models. A notable exception is Daimler, which produced the 12th most vehicles, but produced the third largest number of AFV models. There is a broad disparity between the number of flex-fuel models developed by Volkswagen, Ford, and General Motors and the other companies. This could be because of the ethanol subsidies provided by the US, Brazil, and Sweden (where all three companies have a strong presence).

#### 5.3.1. Leaders and followers

During the study period, there were dramatic increases in the number of AFV models that used hydrogen, electricity, or flex-fuel.

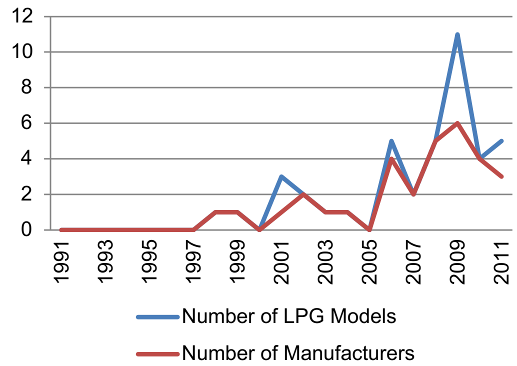


**Fig. 11.** LPG vehicle models.

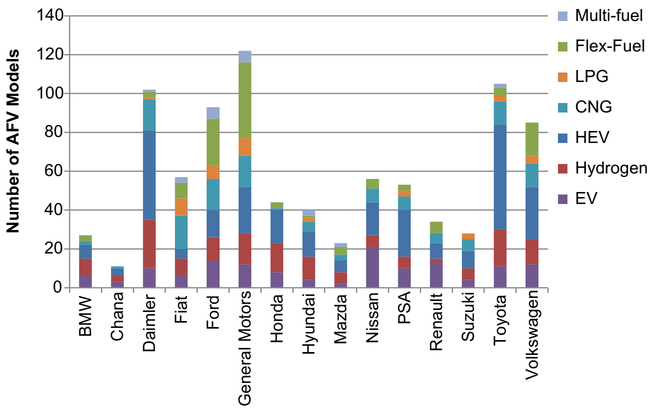


**Fig. 13.** Number and type of AFV models developed by individual incumbent auto makers.

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For hydrogen vehicles this began in 1995, for flex-fuel vehicles 2002 and for EVs 2008. The companies that developed hydrogen vehicle models directly before these periods of dramatic increase were Daimler, Mazda, and Toyota. For flex-fuel vehicle models the early leaders were General Motors and Ford. For EV models they were Ford and Nissan. With the exception of Mazda and hydrogen vehicle models, the early leaders in an AFV technology before a large increase in model presentation went on to have the largest number of models in that technology at the end of the study period. For example, Ford and General Motors (both early leaders in flex-fuel technology) presented 24 and 39 flex-fuel vehicle models respectively. The company with the next highest number of flex-fuel vehicle models was Volkswagen with 17. Toyota and Daimler were among the early developers of HEV models, and went on to develop the greatest number of AFV models in that technology.

## 6. Conclusions and policy recommendations

### 6.1. Conclusions

Our research set out to analyze technological diversity among alternative fuel vehicles that were developed by incumbent firms during an era of ferment. The data showed that the number of models and technological diversity of AFVs steadily increased from 1991 to 2011. From a firm-level perspective, some incumbents focused on specific technologies e.g., Nissan with EV and Toyota with HEV. On the whole, though, automobile manufacturers developed a wide variety of AFVs. Over the entire study period, incumbents showed a preference for competence-enhancing technologies (57% of the AFVs were able to use gasoline or diesel as a fuel source e.g., HEVs and bi-fuel vehicles). However, recently the number of EV models (a competence-destroying technology) has increased at the quickest pace among all AFV types. Our analysis points to a competitive environment that is becoming increasingly uncertain and turbulent, similar to that seen during a technological transition. In addition to these conclusions regarding the industrial dynamics of eco-innovations, our results also provide some material for speculation as to what may occur in a technological transition in the automobile industry.

Based on our analysis and the technology transitions literature, there are three distinct possibilities regarding the future of automobile technology (1) the continued dominance of the ICE, (2) the emergence of a new dominant design, or (3) different technologies successfully competing in markets with high levels of demand heterogeneity. The first two alternatives represent the standard outcome of an era of ferment according to the product life cycle, however there are some elements of eco-innovations and AFVs in particular that could result in the third option. Indeed, Tables 3 and 4 show that multiple AFVs (HEVs and flex-fuel vehicles) can simultaneously compete with ICE vehicles. The situation where no dominant design emerges and different AFVs exist in separate markets would require high levels of demand heterogeneity. We believe that such demand heterogeneity could arise through (1) markets protected through regulation e.g., flex-fuel vehicles in the US, (2) vehicle use e.g., EVs for urban use and CNG vehicles for freight transportation, or (3) fuel availability e.g., plentiful CNG in the US and flex-fuel in Brazil could lead to low fuel costs in those countries. Our analysis of AFV technological diversity indicates that a technological transition in the automobile industry *could* be underway. Additional monitoring of industrial dynamics will help to identify if/how a technological transition is unfolding.

A secondary goal of our article was to use our analysis to inform policy recommendations regarding AFV development and adoption. Our analysis showed that incumbents are developing a wide variety of AFV technologies. Below we provide policy recommendations for each of the AFV eco-innovations in the study depending on its relation to the ICE powertrain (incremental, radical, systemic, or artifactual).

### 6.2. Policy recommendations

As incumbents seek to satisfy their current customer base and compete in the automobile market using the dominant design they naturally develop eco-innovations that are incremental and artifactual. Economy wide policies targeting an environmental goal e.g., lower emissions, are an appropriate way to stimulate those types of eco-innovations.

Supportive policies are often required in order to stimulate the development and ado0ption of radical eco-innovations (Kemp, 1997). Therefore, technology-specific policies are (were) appropriate to promote the development of HEVs. Governments e.g., the US and Japan, have been subsidizing the purchase of HEVs for years. This policy approach along with increases in gasoline price and technological advancements have helped to establish a sustained market for HEVs. With a functioning and self-supporting market for HEVs, it is probably not necessary to continue policy support of the technology. Additionally, because HEVs have lower emissions and greater fuel efficiency than comparable ICE vehicles, they will naturally benefit from economy wide policies with environmental goals.

Innovations that are systemic and incremental are largely limited by fueling infrastructure. Even with this limitation, functioning niche markets for LPG and CNG vehicles have emerged. These are usually found in industries that have fleets of automobiles and can distribute fuel to their vehicles e.g., airports or public transport companies. If policymakers decide to support AFVs that represent systemic and incremental eco-innovations to the ICE, (LPG, CNG, or flex-fuel), then they should develop policies to either directly support the construction of infrastructure or facilitate infrastructure coordination between car manufacturers and energy companies.

Government policies have been successful in stimulating the development of radical innovations such as hydrogen and electric vehicles, but this has not yet translated to true commercial success for those technologies. The number of production EVs available indicates that it is in a different phase of commercialization than FCEVs. Policies to support EVs should focus on adoption and infrastructure while FCEV policies should target continued development. Adoption policies entail both supply and demand-side measures. Supply-side environmental performance regulations (technology-forcing) should be continued, e.g. stricter emissions and fuel efficiency policies. Demand-side policies can be direct financial incentives for early adopters or information centers that explain the actual costs and benefits of owning a hydrogen or electric car. However, both policy approaches have their drawbacks. Technology-specific policies do function to distort the market and should be used cautiously. Governments have to be cognizant that the demand for AFVs might collapse after the end of demand-side policies if the technology has not advanced enough to create a sustainable market. If supply-side measures are too onerous, e.g. ZEV mandate, then businesses might rebel through legal recourse. Infrastructure policies protect the early stages of commercialization of systemic innovations and are necessary for hydrogen and electric vehicles. The continued development of EVs and FCEVs can also be supported through grants and low-interest loans to firms that are focusing on that technology.

In summary, we identify three important policy approaches to encourage the move toward sustainable automobile transportation. (1) Economy wide policies drive development of all types of AFV

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powertrains especially incremental innovations. (2) Policies to encourage construction of fuel or charging infrastructure are appropriate to determine if there exists a market for incremental systemic AFVs. (3) Technology-specific policies are necessary for the development and adoption of radical systemic AFVs.

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