Paper to be presented at the DRUID Academy 2012

on

January 19-21
at
University of Cambridge /The Moeller Centre

Incumbent firm behavior regarding multiple emerging technologies: A prototype and production model analysis of the automobile industry

William Stanley Sierzchula
Delft Technical University
Transportation Policy and Management
willsierzchula@yahoo.com

Sjoerd Bakker
Delft Technical University
TPM
s.bakker-1@tudelft.nl

Abstract

? Name - William Sierzchula ? Affiliation - TU Delft ? Year of enrollment ? 2010 ? Expected final date ? July 2014 ? E-mail address ? W.S.Sierzchula@tudelft.nl

Introduction

There is a robust literature that addresses industrial change through emerging technologies. Initially this literature studied examples where incumbent firms were overtaken by startup firms (Foster, 1986; Christensen, 1997). Innovation literature has recently focused on identifying examples where incumbents were able to successfully incorporate a disruptive innovation into their business plan (Jiang et al., 2010). The above research focused on the industrial influence of individual innovations. My study examines incumbents? behavior as they attempt to remain competitive while confronted with a large number of diverse emerging technologies.

Theory

Christensen (1997) showed that incumbent firms across a variety of industries were more preoccupied with the expectations and demands of their current customers than noticing the opportunities that existed through new innovations. However Ahuja and Lampert (2001) identified some of the behavior of incumbent firms that have successfully navigated industrial change. These concepts provide a context for understanding incumbent strategies (both successful and unsuccessful) when presented with emerging technologies.

Method

This research utilizes a prototype/production model analysis to examine the kind of AFVs the 15 largest incumbent

automobile manufacturers have developed over the past 20 years. This analysis gathered information about ~ 800 production or prototype alternative fuel vehicle (AFV) models from 1991 to 2011 that used any of five different fuel types (electricity, compressed natural gas, liquefied petroleum gas, hydrogen or ethanol). This research used cross-sections of different types of information from the dataset in order to better understand the development of AFV technologies by incumbent firms. This allowed for three different ways of viewing the data; from an industry, firm and technology prospective.

Results

The annual number of AFV models increased during the study period. There was a sequential rise and fall in the number of EV models, hydrogen vehicle models and flex-fuel vehicle models that were presented by auto makers. EVs are the current AFV technology du jour. Over the study period, there was an increase in the variety of AFV technologies that manufacturers presented in a given year. There were two basic periods of development for AFV technologies. The first consisted of a few manufacturers making a small number of models. The second entailed an increase in the number of manufacturers and models per manufacturer. Firms that engaged in early development of an AFV technology often presented the most models with that technology by the end of the study period.

Conclusion

Technologies appear to go in and out of style when looking at the model history of EV, hydrogen vehicles and flex-fuel vehicles. As a whole, incumbents are uncertain about the future of the automobile industry as is evident by the increase in the number of models with different AFV technologies they presented during the study period. The largest manufacturers are attempting to be a ?first mover? in the AFV market instead of waiting for a successful commercial product to appear and then developing that particular type of technology.

References

Ahuja, G. & Lampert, C. 2001. Entrepreneurship in the large corporation: A longitudinal study of how established firms create breakthrough discoveries. Strategic Management Journal, 22: 521 ? 543.

Christensen, C. 1997. The Innovator?s Dilemma. Harvard Business School Press: Boston, MA.

Foster, R. 1986. Innovation: The Attacker?s Advantage. London, Macmillan.

Jiang, L., Tan, J. and Thursby, M. 2010. Incumbent firm invention in emerging fields: evidence from the semiconductor industry. Strategic Management Journal, 32: 55 ? 75.

Jelcodes:O32,-

Incumbent firm actions regarding multiple emerging technologies: A prototype and production model analysis of the automobile industry

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). 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 during this period will play an important role in determining the future of automobile technology. Our research explores the actions of incumbents regarding the development of alternative fuel vehicles (AFVs) and the influence this could have on short-term competition of powertrain technologies in the automobile industry.

Since 1990, there has been a great deal of activity regarding the development of AFVs specifically through government policies, technological developments and partnerships between government agencies and firms. This had led to a situation where AFVs are becoming more competitive with petrol-fueled ICE vehicles (IEA 2009). Government policies that have encouraged the development of AFVs include California's Zero Emission Vehicle (ZEV) mandate in 1990, the 2005 US Energy Policy and the 2009 EU emissions regulation (Bedsworth & 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 encouraged firms to shift focus to other alternative fuel powertrains such as hybrid-electric (Dijk & Yarie 2010; Pilkington and Dyerson, 2006). Firms have been developing technologies that are crucial to the competitive nature AFVs. Examples include Ballard Power System with hydrogen fuel cells and Panasonic with batteries (Hall & Kerr 2003; Magnusson & Berggren, 2011). These firms have formed partnerships with large incumbent auto manufacturers (Ballard with Daimler and Panasonic with Toyota) raising the profile of new powertrain technologies (van den Hoed 2006). As technologies improve, niche markets have opened up where AFVs have a competitive advantage over petrol-fueled ICE vehicles (van Bree et al., 2010). The Partnership for a New Generation of Vehicles (PNGV) and US Drive are examples of partnerships between governments and large auto manufacturers which have encouraged the development of AFVs (US DoC, 1998; US DoEa, 2011). These partnerships allow for better communication, coordination and utilization of resources regarding AFV development. In part due to government policies, cooperative programs and technological improvements, incumbents have been increasing the proportion of alternative fuel technologies such as electric, hybrid-electric and hydrogen vehicles in their patent portfolio (Oltra & Saint Jean, 2009; Bakker, 2010). Recent market developments also indicate that large auto makers now view the EV market as a commercial opportunity instead of a regulatory requirement (Magnusson & Berggren, 2011).

The goal of our research is to identify which policies geared toward incumbent auto manufacturers are appropriate to stimulate the development and eventual adoption of sustainable transportation. Previous research looking at industrial change has largely focused on competition between the dominant design and one emerging technology (Abernathy & Utterback, 1978; Anderson & Tushman, 1990; Christensen, 1997). This presents a scientific gap within the product life cycle literature of how incumbent firms select an innovation for development when there are multiple technologies competing with the dominant design during a period of uncertainty (such as that in which the automobile industry currently finds itself). The research question which will address this gap is *what are the actions of incumbent automobile firms when multiple alternative fuel powertrain technologies are competing with the petrol-powered internal combustion engine*. Answering this research question entails addressing three research sub-questions - how have incumbents developed alternative fuel powertrains from an (1) industry, (2) technology and (3) firm perspective? Additionally, because AFVs are eco-innovations this study will also address a fourth research question. (4) How does the product life cycle pertain to eco-innovations such as AFVs?

This paper is organized as follows. Following this introductory chapter is a section (section 2) that briefly identifies the different types of AFV technologies that will be studied in this research, policies that have influenced their development and sales statistics. Section 3 lays out elements of the product life cycle and eco-innovation concepts that provide the theoretical foundation for this research. The methods 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. Lastly, section 6 includes a brief conclusion and discussion that highlights the main points of this research along with relevant policy suggestions.

2. Challenges facing alternative fuel vehicles and policies

In order to provide a thorough analysis of incumbent actions regarding AFV development, it is necessary to have some background information on the competitive environment of automobiles. The section below identifies the technologies, policy frameworks and sales figures regarding AFVs within the automobile industry. It also details how powertrain technologies differ from one another relative to the petrol-fueled ICE vehicle.

2.1 Alternative fuel vehicles

The alternative fuel vehicles included in this research predominantly differ from the conventional design (petrol-fueled ICE vehicle) in terms of their powertrain technology. Table 1 below outlines these innovations in terms of the fuels that they use, barriers that limit their adoption and advantages relative to the petrol-fueled ICE automobile. In table 1, BlueMotion is an innovation developed by Volkswagen which makes petrol-powered vehicles more fuel efficient. It represents a minor improvement to the existing technology. Other powertrain innovations included in this table are: flex-fuel, Liquid Natural Gas (LNG), Compressed Natural Gas (CNG), H_2 ICE, Hybrid Electric Vehicle (HEV), EV, and Hydrogen Fuel Cell Electric Vehicle (FCEV). The three main takeaways from table 1 are that most alternative fuel technologies offer lower emissions and fuel costs, but face barriers of high costs and a lack of fuel infrastructure.

	Fuel	Barriers	Advantages to ICE
BlueMotion	Petrol	None	Increased fuel efficiency
Flex-Fuel	Petrol or E85	Lack of flex-fuel	Lower emissions, decreased reliance on petroleum
LNG	LNG	Lack of LNG infrastructure	Lower emissions, lower fuel costs
CNG	CNG	Lack of CNG infrastructure	Lower emissions, lower fuel costs
H_2 ICE	Hydrogen	High emissions, high cost, low driving range	Decreased reliance on petroleum
HEV	Petrol	High cost, vehicle performance and reliability concerns	Lower emissions, lower fuel costs
Plug-in HEV	Petrol or Electricity	High cost, lack of refueling infrastructure	Lower emissions, lower fuel costs
BEV	Electricity	High cost, long charge time, limited driving range, lack of refueling infrastructure	Lower emissions, lower fuel costs
FCEV	Hydrogen	High cost, reliability concerns, lack of infrastructure	Lower emissions, potentially low fuel costs

Table 1. Fuels, barriers and advantages of alternative fuel powertrains (Yu et al., 2010; US DoE, 2011b; US DoE, 2011c; Mom, 1997; Bedsworth & Taylor, 2007; Bakker, 2010; Daimler, 2010)

Table 2 highlights how powertrain innovations are different from petrol-fueled ICE vehicles. Henderson and Clark (1990) provide a framework for understanding innovations based on their relation to core components and linkages between those components (product architecture). This creates four categories of innovations (incremental, radical, modular and architectural). Incremental innovations reinforce both elements. Radical innovations involve changes to both core concepts and linkages. Modular innovations have changes to core components, but not linkages between those components. Architectural innovations reinforce core concepts but change linkages. For this research, changes of core components will be relative to the petrol-fueled ICE. Changes in linkages will be relative to fuel infrastructure. Figure 1 provides a graphical description of where the powertrains fall relative to the petrol-fueled ICE which is given in table 2.

	Changes to product core components	Changes to product architecture
BlueMotion	Incremental - more efficient engine	Modular - changes to the engine
Flex-Fuel	Incremental - slight engine modifications	Architectural - ethanol fuel infrastructure
LNG	Incremental - slight engine modifications	Architectural - LNG fuel infrastructure
CNG	Incremental - slight engine modifications	Architectural - CNG fuel infrastructure
H_2 ICE	Incremental - slight engine modifications	Architectural - H_2 fuel infrastructure
HEV	Radical - battery/ICE propulsion	Modular - powertrain changes
Plug-in HEV	Radical - battery/ICE propulsion	Architectural - electricity infrastructure
BEV	Radical - only battery propulsion	Architectural - electricity infrastructure
FCEV	Radical - fuel cell propulsion	Architectural - H_2 fuel infrastructure

Table 2. Alternative fuel powertrain innovations relative to the petrol-fueled ICE

Figure 1 shows that AFV powertrains do not necessarily neatly fit into Clark and Henderson's innovation framework. Volkswagen's BlueMotion innovation is the most similar to the dominant design of the petrol-fueled ICE. Among AFV technologies in this research, the flex-fuel powertrain is an incremental innovation in that it represents a small change to the ICE, but also an architectural innovation because it can use an ethanol-petrol fuel mixture (Yu et al., 2010). HEV is a modular innovation because it represents fairly dramatic changes to the ICE but no significant changes to fuel infrastructure. The plug-in HEV powertrain, however does require new fueling infrastructure (additional charging stations), so it also includes changes in linkages between core components. EV and hydrogen (FCEV) powertrains are radical innovations because both the ICE and fuel infrastructure change dramatically (Pohl & Slmquist, 2010; van den Hoed, 2006). H_2 ICE, LNG and CNG are architectural innovations, because the ICE does not change significantly but new fuel infrastructures are required.

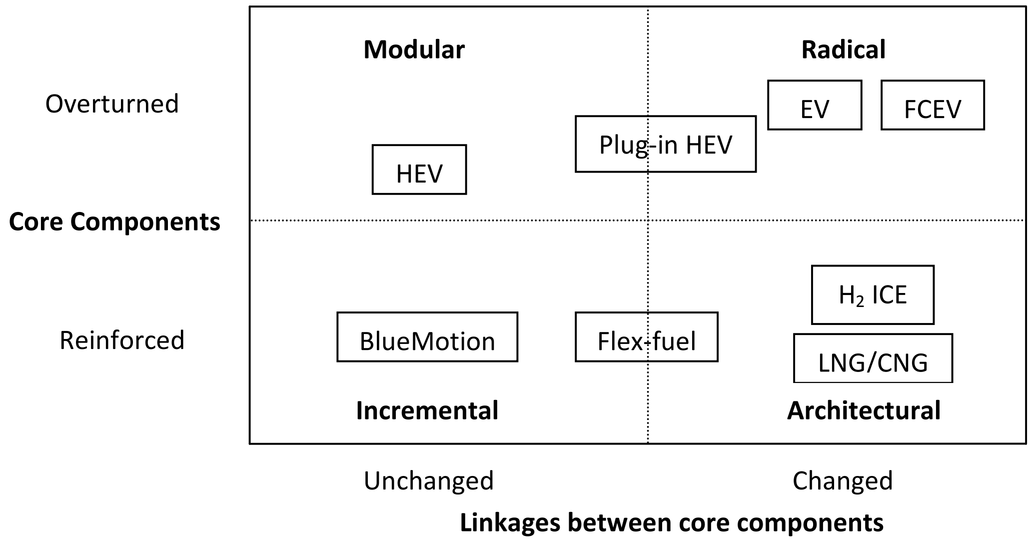

Figure 1: Authors' rendering of the powertrain innovations relative to the petrol-fueled ICE (adapted from Henderson and Clark, 1990)

Incumbents are quite good at implementing incremental innovations, but can have difficulty with developing and selling radical innovations (Christensen, 1997). The relationships identified in Figure 1 play a role in determining how incumbents approach the development of different AFV technologies. Government policies also influence the approach that auto manufacturers take toward vehicle development. A description of some of these policies is provided below.

2.2 Alternative fuel vehicle government policies

Eco-innovations differ from other types of innovations in that they provide a reduced environmental impact when compared to existing technological alternatives (Rennings, 2000). Because of this, governments encourage their development through targeted policies. This section of the paper provides examples of different categories of AFV policies: demand-side (marketing and subsidies), supply-side (environmental regulation and low-interest loans), infrastructure, land-use planning and public transport (adapted from Blok and Van Wee, 1994). This list of policies is by no means meant to be exhaustive, but rather illustrative in the ways that governments support the development AFVs. Such policies can be implemented on different government levels e.g. cities, states, countries and multi-country regions.

One approach attempts to stimulate demand through consumer-facing regulation (pull policies) (Cleff & Rennings, 1999). Japan's subsidy to buyers of HEVs and EVs that was in effect from 1998 – 2003 is an example of a pull policy (Jari, 2003). The US Energy Policy Act of 2005 was a similar policy that provided tax credits to buyers of HEV. By lowering the price of AFVs, the Japanese and US governments encouraged their purchase. France uses a "bonus-malus" approach that provides financial incentives for fuel efficient vehicles and tax penalties for fuel inefficient vehicles (French Embassy 2011). Municipalities have used a different approach by implementing policies that support AFV adoption by increasing the convenience of their ownership. Since 2003, HEV and EV have been exempt from the congestion tax upon entering the downtown London area (Transport for London, 2011). AFVs are new technologies bringing with them a level of uncertainty, which discourages consumers from being early adopters (Metcalf, 1994). Some countries such as the Netherlands provide information centers to assist consumers in making informed transportation decisions (Elektrisch Vervoer Centrum, 2012).

A second approach targets AFV production through environmental regulations and low-interest loans to suppliers (push policies) (Cleff & Rennings, 1999). Examples of environmental regulation include EU emissions standards, the California ZEV mandate and the US Corporate Average Fuel Economy (CAFE) regulations. EU emissions standards call for a gradual lowering of manufacturer fleet average $C0_2$ emissions towards 130 g/km in 2015 and 95 g/km in 2020 (European Commission, 2009). The ZEV mandate from 1990 required that a percentage of all vehicle sales by large-volume auto makers in California emit zero emissions[1]. This percentage of ZEV sales was set at 2% from 1998 – 2000, 5% in 2001 and 2002 and 10% thereafter (Bedsworth and Taylor, 2007). CAFE regulations have functioned to increase the average fuel economy of vehicles in the US. Auto manufacturers can meet CAFE regulations by developing and selling low-emissions vehicles such as HEV and EV to help offset low fuel economy of other automobiles. In addition to forcing innovation through regulation, policies can also entice firms to develop AFV technology through attractive pricing. US subsidies for ethanol production have reduced the price of ethanol-based fuels (flex-fuel) and created a situation where flex-fuel is significantly cheaper than gasoline (E85prices, 2011). The current system of ethanol credits provides $0.45 per gallon for blending ethanol with gasoline for sale and has been in place since 2005 (CBO, 2010). Supply-side policies can also target individual firms. The US government provides financial support to companies that are developing AFV technology through the Advanced Research Projects Agency-Energy (ARPA-E). The agency provided low-interest loans to HEV maker Karma Fisker and EV maker Tesla in order to support their operations (US DoE, 2010).

Infrastructure policies include efforts to provide refueling stations (e.g. Hydrogen, Electricity, and CNG) to AFV users. This attempts to provide a situation where more extensive use of AFVs is not limited by a lack of refueling stations. Land use policies include drivers in Maryland being able to drive EVs in High Occupancy Vehicle (HOV) lanes with only one individual in the vehicle (DoE 2011d). In Amsterdam where parking is expensive and limited, free charging and parking spots have been reserved specifically for EVs

[1] The ZEV mandate was severely weakened in 2003 to require fewer emissions-free vehicles.

(Nissan, 2010). Public transport policies have allowed governments to influence the adoption of AFVs by acting as a consumer e.g. hydrogen and electric buses in municipal fleets (Daimler, 2012; goed bezig bus, 2012; US DoE 2005). These policies are largely pilot projects to determine the financial and environmental effect of AFVs as public transportation. Because of the size and scope of their operations, governments can provide a significant level of demand for eco-innovations. Exposing government workers to eco-innovations also helps to alleviate some of the uncertainty that is inherent in the use of a new product. By becoming familiar with eco-innovations through their employment, government workers might be more inclined to purchase environmentally-oriented products for their residential use.

2.3 Alternative fuel vehicle sales

As identified in figure 1, alternative fuel powertrains represent incremental and radical innovations to petrol-fueled ICE vehicles. The section above provides some basic information about the technological make-up of these different powertrains, 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 1 supplies the number of AFVs that were sold, leased or converted in the US from 1999 - 2008. Table 2 gives AFV production statistics for Japan from 2000 to 2009. Trends in table 1 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. In table 1, flex-fuel vehicles constituted the largest portion of AFVs with 11% of all automobiles in 2008 followed by HEVs at 3% in 2008. The other AFV technologies comprised a very small proportion of total vehicle sales, leases or conversions.

Table 2 provides a different picture of a country’s production approach to AFVs. 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 1,706 in 2009, which could indicate a developing interest in the technology.

A significant difference between the two tables is that the US had much higher numbers of flex-fuel vehicles than Japan. Both countries had increases in the number of HEVs during the 2000s, with the technology representing the most numerous AFVs in Japan and second most numerous AFVs in the US (behind flex-fuel vehicles). The EV increase and decrease in the US was perhaps due to the implementation of the ZEV mandate in 1990 and its subsequent weakening in 2003.

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
All Vehicles	16,043,303	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
CNG	13,425	9,501	11,121	8,988	6,122	7,752	3,304	3,128	2,487	4,440
EV	1,957	6,215	6,682	15,484	12,395	2,200	2,281	2,715	3,152	2,802
Flex-fuel	426,724	600,832	581,774	834,976	859,261	674,678	743,948	1,011,399	1,115,069	1,175,345
HEV	17	9,350	20,282	36,035	47,600	84,199	209,711	252,636	352,274	312,386
Hydrogen	0	0	0	2	6	31	74	40	63	63
LPG	5,955	4,435	3,201	1,667	2,111	2,150	700	473	356	695

Table 1: Vehicles sold, leased or converted in the US from 1999 – 2008 by powertrain type (DoE 2011a)

	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	2,447	4,028	3,972	3,852	3,265	3,066	3,091	2,175	2,379	1,197
EV	150	183	83	49	17	0	0	0	0	1,706
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	2,183	3,157	2,194	3,244	3,121	1,799	2,438	874	609	450

Table 2: Vehicles produced in Japan from 2000 – 2009 by powertrain type (Jama 2011)

3 The role of incumbents in the product life cycle

The product life cycle literature provides the theoretical foundation for analyzing incumbent development of AFV models. Researchers have traditionally utilized *ex post* case studies as a way to analyze industrial change and the emergence of new technologies (Anderson & Tushman, 1990; Henderson & Clark, 1990; Abernathy & Utterback, 1978; Clark, 1985). One theoretically important element of our research is that the competition between petrol-fueled ICE vehicles and AFVs is currently underway. Thus, it is not an *ex post* analysis because there is an element of uncertainty about which alternative fuel powertrain will eventually emerge or if the petrol-fueled ICE vehicle will remain the dominant technology. This theoretical chapter first provides a general description of the product life cycle and its relevance for this research. Following this background information is a section that more specifically outlines the role of incumbents in the process. Finally, the theoretical significance of AFVs as eco-innovations is explored within the context of the product life cycle.

3.1 The product life cycle

The product life cycle refers to the way that industries change over time through innovation (Klepper, 1996). Abernathy & Utterback (1975, 1978) are some of the most influential researchers in this area of research based on their notion of a dominant design. The process of the product life cycle is largely in reference to a dominant design that consists of more than 50% of a market (Abernathy & Utterback, 1978). There are two distinct periods within the product life cycles; a period of incremental innovations and an era of ferment (Anderson & Tushman, 1990). The period of incremental innovations is marked by a small number of principal incumbents making changes to the dominant design (Klepper, 1996). These changes are generally minor and help improve the technology's performance relative to existing customer and industry expectations. An era of ferment occurs when a radical innovation disturbs the market supremacy of the dominant design. During an era of ferment, the variety of different technologies and the number of competing firms increase. Through initial demand from a niche market and a steep development curve, successful radical innovations are able to gradually outcompete existing technologies in larger and larger markets. From an era of ferment, a new dominant design arises beginning the cycle anew. The emergence of a dominant design from an era of ferment is marked by a decrease in technological variety and the number of competing firms. During this time, companies start to develop standards for and begin making incremental improvements to the dominant design. A classic example of the product life cycle is the series of innovations which took place as ships evolved from being powered by wind to being powered by mechanical engines (Geels, 2001). In this ship example, the introduction of steam-powered engines was the radical innovation because it presented a different way to propel a vessel. Suarez (2004) has created a framework describing five different phases of the product life cycle: (1) R&D buildup, (2) technical feasibility, (3) creating the market, (4) decisive battle and (5) Post-dominance.

3.2 Incumbents

Radical innovations bring with them a level of uncertainty. This uncertainty has had a big impact on the approach that incumbents have taken toward radical innovations (Christensen, 1997). In some instances, incumbents have successfully incorporated radical innovations into their business strategies and maintained market share (Abernathy & Utterback, 1978). In other instances, incumbents neglected innovations and startups emerged as the market leaders (Foster, 1986). In yet other cases, innovations never developed as serious competitors to current technology e.g. the unsuccessful Apple Newton (Christensen, 1997).

In the product life cycle, the research is ambiguous. In some studies, incumbents are predisposed toward focusing on the development of incremental innovations while startup firms create a greater proportion of radical innovations (Hill & Rothaermel, 2003). Chandy and Tellis (2000) on the other hand, found that incumbents and large companies have produced a larger proportion of radical innovations than startup firms from World War II to 2000 (the date of their study). Thus, the David versus Goliath story of the scrappy startup besting the powerful incumbent through new technology makes for an appealing read, but is not necessarily representative of what happens during technological transitions. However, both the continued success of incumbents and the emergence of startup firms are important alternatives to keep in mind when considering the Product life cycle. Numerous researchers especially Christensen (1997) and Foster (1986) chronicle how incumbents are generally unable to grasp the importance of a new innovation and do not make the necessary changes to be competitive in the developing market. One of the reasons why incumbent firms have failed to sufficiently identify and develop emerging technologies is because of their customer focus. Using the disc drive industry as an example, Christensen (1997) showed that many incumbent firms were too preoccupied with the expectations and demands of their current customers to notice the opportunities that existed through new innovations. When assessing the potential value of an innovation, companies do not know whether it will be successful and disrupt the industry or if it is merely a lower performing alternative to existing technology (Adner, 2002). The combination of low profit margins and lack of appeal to current customers encourages incumbents not to initially pursue the technology. Additionally, incumbents refrain from investment in radical innovations entirely for fear of cannibalizing their current customer base (Reingaum, 1983). For this reason, incumbents often continue to develop and market the prevailing technology while paying little regard to the emerging radical innovation.

However, some incumbents have also led the way in developing radical innovations such as Motorola with cell phones and IBM with personal computers. There are also many examples of incumbent firms that have successfully evolved after the introduction of a radical innovation (Rothaermel, 2001; Ahuja & Lampert 2001). Incumbent companies that develop or successfully incorporate radical technologies often invest in basic research, allow for a long technological development periods and have a diversity of alliance partners (Jiang et al. 2010). Incumbents may also be inclined to target niche markets with new innovations in order to avoid cannibalizing their existing customer base (Day & Schoemaker, 2000).

3.3 Eco-innovations and the product life cycle

While there is not a specific theory regarding the development of eco-innovations per se, eco-innovations do have unique aspects which could influence their performance in the product life cycle. On a base level, eco-innovations incorporate environmental benefits in the price and performance value proposition that consumers consider before making a purchasing decision (Janssen and Jager, 2002;

Faber & Frenken, 2009). This extra element creates a new class of eco-consumers that value the environmental nature of products and are willing to pay a premium for eco-innovations (Jay, 1990). However, the importance of environmental benefits relative to a technology's price and performance varies drastically among consumers. For example, the majority of individuals who purchase vehicles indicate that they value environmental benefits, but they often are not willing to pay a higher amount for more environmentally friendly automobiles (Caulfield et al., 2010). Another crucial element of an eco-innovation is the nature of its environmental benefits and the fact that they are not exclusive to its consumer. Because society as a whole gains from the cleaner environment that eco-innovations provide, many governments encourage their development through regulation such as subsiding their purchase and taxing polluting alternatives (Cleff and Rennings, 1999; Rennings, 2000).

Government regulation and consumer preferences influence the type of vehicles that manufacturers develop. Auto manufacturers attempt to produce vehicles that satisfy consumer demand while meeting regulation requirements and taking advantage of government support. The AFVs that manufacturers have developed provide insight into how they intend to remain competitive in a transitioning automobile market. The product life cycle helps to understand some of the dynamics that are influencing incumbents' development of low-carbon alternatives to the petrol-fueled ICE automobiles. Eco-innovation concepts identify some of the issues that are specific to AFVs that firms consider as they determine their actions in an uncertain automobile market.

4 Methods

Our analysis is attempting to identify the actions of incumbent automobile firms when multiple powertrain technologies are competing with the petrol-powered internal combustion engine. This can be accomplished by answering three sub-questions - how have AFVs developed from an industry, technology and firm perspective? A fourth research question looks at how AFVs as examples of eco-innovations, performed in the product life cycle relative to the expectations of a typical innovation. As tables 1 and 2 describe, the number of AFVs that have been produced and purchased varies widely by technology. In order to examine incumbent manufacturers' actions regarding emerging technologies this research has opted to do an analysis of prototype and early production models instead of focusing only on vehicle sales. This allows for a better comparison of how incumbents have approached the development AFV technologies that are in vastly different stages of commercialization e.g. flex-fuel and hydrogen vehicles, than by merely looking at sales figures. This study analyzes AFV prototype and production model data in different ways to answer the individual research questions identified above.

Information about prototype and production models came 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 petrol to an alternative fuel by a 3rd party company was not included in the vehicle database. A study period of 1991 to 2011 was used for this research because 1991 captures the influence of California's ZEV mandate on AFV development. This study gathered information about 884 production and prototype AFV models that used any of five different alternative fuel types (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[2] where petrol and electricity both provide power to the automobile. In addition to AFVs that employed one fuel type, there were also examples of models that used two or three different fuels. These are referred to as multi-fuel vehicles and are analyzed as a group in the results section. Most of these multi-fuel vehicles combined petrol with an alternative fuel. However, there were 23 models that combined two or more alternative fuels e.g. a vehicle that uses CNG and flex-fuel. The specifics of those vehicles are detailed further in the results section.

Data for the following characteristics were collected for each model: manufacturer, model, fuel type, classification (prototype or production) and introduction date (when it was presented to the market). 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 vehicles. 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 has five vehicles in the database (one for the prototype, one each of the three generations with NiMH hybrids and one for the lithium-ion version). For companies such as GM that rebrand the same vehicle under different subsidiaries e.g. GMC Sierra and Chevrolet Silverado, only one version was included in the final data set.

Different analyses of the prototype and production model database allows for viewing the development of AFVs from an industry, technology and firm perspective. The industry overview 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 and production status. The technology perspective provides a yearly representation of the number of AFV models and manufacturers for each of the different powertrain types. The firm perspective presents the number of AFVs and type of powertrain technologies that each of the 15 firms have developed. The performance of AFVs as an eco-innovation within the product life cycle will be determined by comparing AFV industry-level data to the typical evolutionary pattern described by Suzrez (2004).

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. The number of prototype or production models developed by auto manufacturers can be

[2] This research defines a hybrid electric vehicle (HEV) as using both petrol (diesel or 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.

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 this research is limited to public actions by manufacturers. Companies could conduct important or extensive private research, and those actions would not appear in this research.

5 Results

5.1 Industry Overview

Figure 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 amount. Figure 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. Figure 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. Figures 2, 3 and 4 indicate that incumbents' are uncertain about which technology will be successful, but they are also becoming more aggressive in their AFV strategies. A larger number of incumbent auto manufacturers are developing more AFV models with a greater variety of powertrain technologies.

Table 3 shows that there were more prototype models (507) than production models (377) among the vehicles studied. Models that used incremental powertrain innovations (LPG, CNG and flex-fuel) were much more likely to have a high proportion of production models than models that used more radical powertrain innovations (hydrogen, hybrid and electric vehicles). Hybrid and electric vehicles 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. A significant number of models that used incremental technological innovations and others that used radical technological innovations both appeared in the same year throughout the study period. This indicates that auto manufacturers as a whole are incorporating both types of innovations in their strategies regarding AFV development.

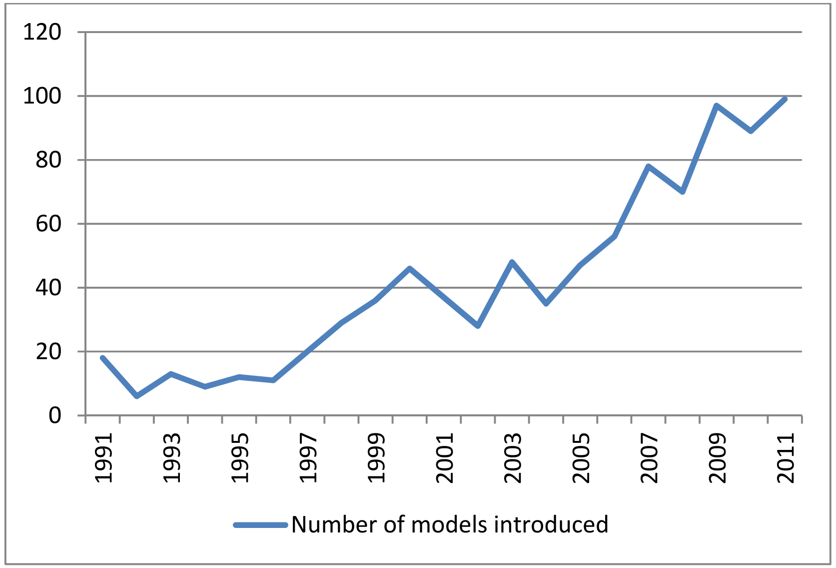

Figure 2: Number of AFV models introduced from 1991 – 2011

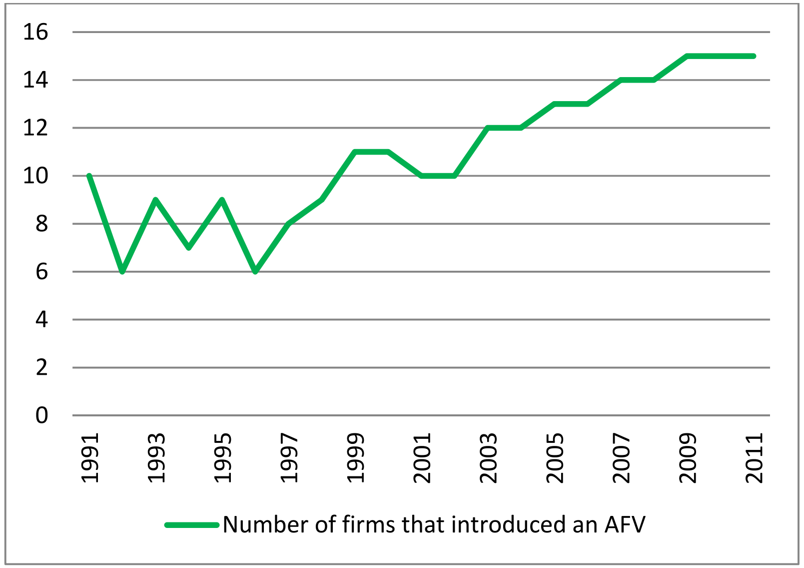

Figure 3: Number of firms that introduced an AFV model

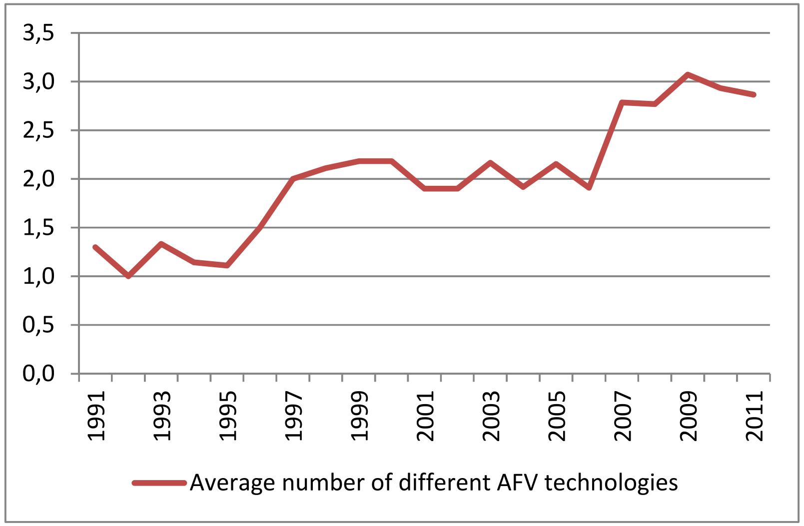

Figure 4: Average number of different AFV technologies presented by manufacturers in a given year

	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%)

Table 3: AFVs according to prototype or production status.

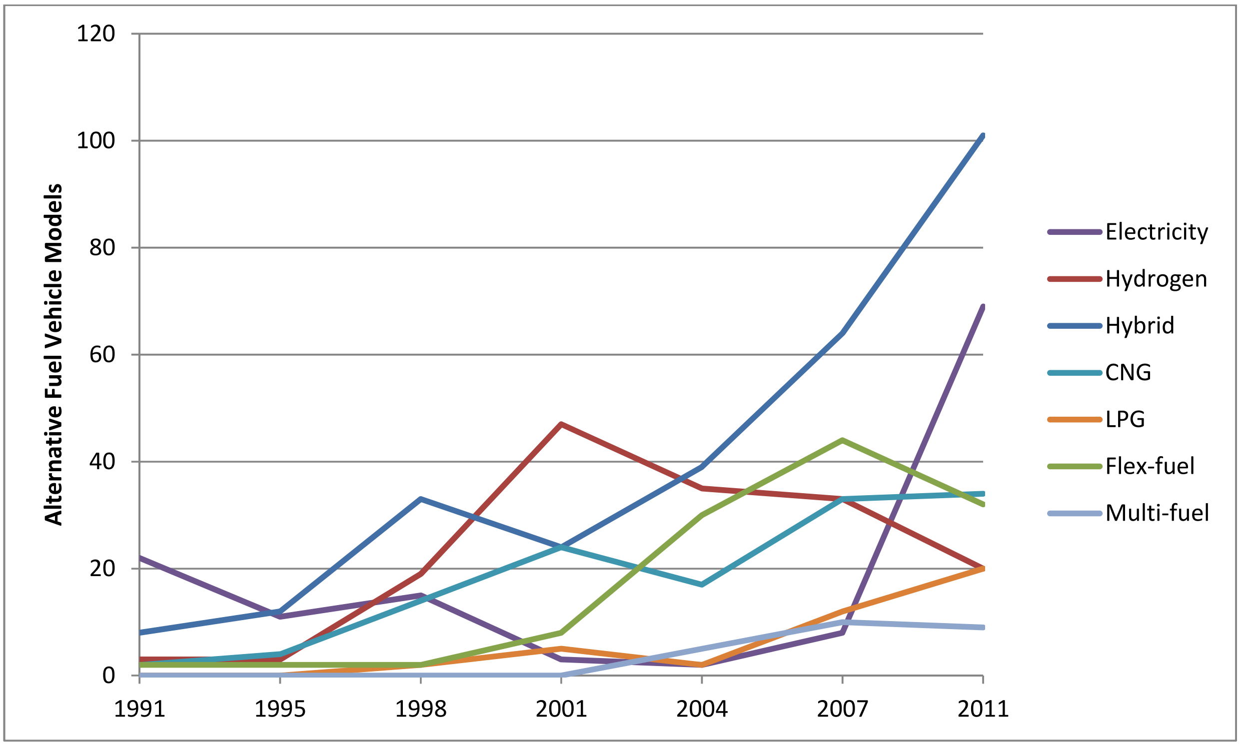

Figure 5: Moving 3 year average of AFV models from 1991 to 2011.

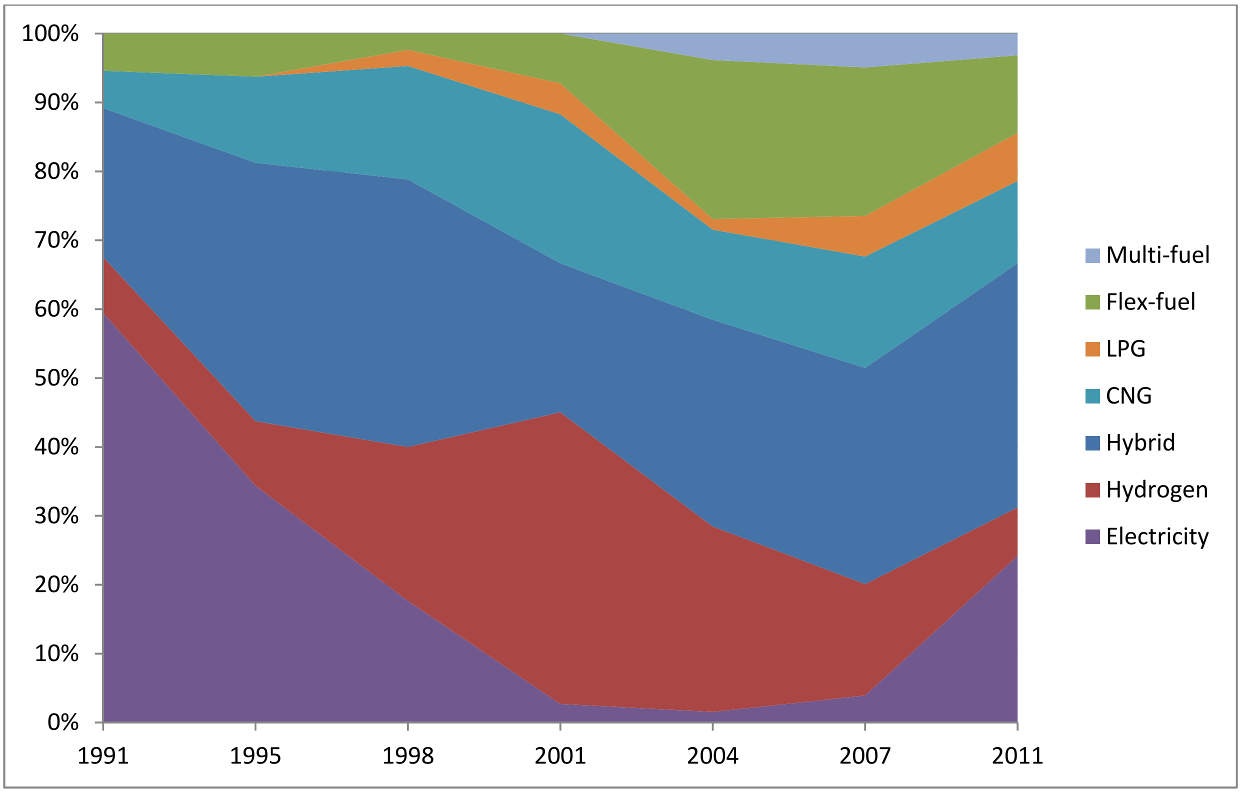

Figure 6: Proportion of AFV models throughout the study period according to technology

5.2 Technology overview

Figure 5 shows the three year average of the number of models that were presented for each AFV technology. Some long-term and short-term trends become noticeable upon inspection of Figure 5. It appears that the auto industry goes through cycles where particular AFV technologies become popular and then interest in those innovations declines. This trend is applicable to hydrogen and flex-fuel AFVs. EVs have seen a similar rapid increase in the number of models, but future development of EV models by auto manufacturers is uncertain. For a long-term pattern, the number of HEV models introduced in a year has increased over the study period. Figure 5 provides a generalization of AFV trends. The annual data may show a more nuanced pattern. For example, flex-fuel vehicles had a much more dramatic rise and fall than is indicated in this graph. A detailed description of AFV trends is available in figures 7 - 12 that address individual technologies.

Figure 6 identifies trends in the proportion of AFV models constituted by different technologies for a given year during the study period. Examples of this include the large proportion of EVs during the early 1990s, followed by the large proportion of hydrogen and ethanol models during the early and mid 2000s. EVs once again increased in their proportion of all AFVs toward the end of the 2000s. These trends support the idea that manufacturer interest in AFV technologies often rise and fall. Regardless of the performance of other AFV technologies, HEVs were consistently between 20% and 30% of all models throughout the study period. LPG and multi-fuel AFVs occupied a small proportion of all models.

Figures 7 through 12 show the number of manufacturers and models with AFV technologies that were introduced from 1991 – 2011. Even though figure 2 shows that the annual number of AFV models introduced has increased, figures 7 – 12 indicate that this was not the case for all technologies. The development of CNG, HEV, and LPG 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 their vehicle lineup. However as a whole, the number of models using those technologies displayed a general increase during the study period. Flex-fuel, hydrogen vehicles and EVs displayed a different path of development. Flex-fuel and hydrogen AFVs exhibited more of a boom and bust scenario with 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. This can be seen most clearly in the sequential rise and fall of hydrogen and flex-fuel vehicle models and the recent dramatic rise in the number of EV models.

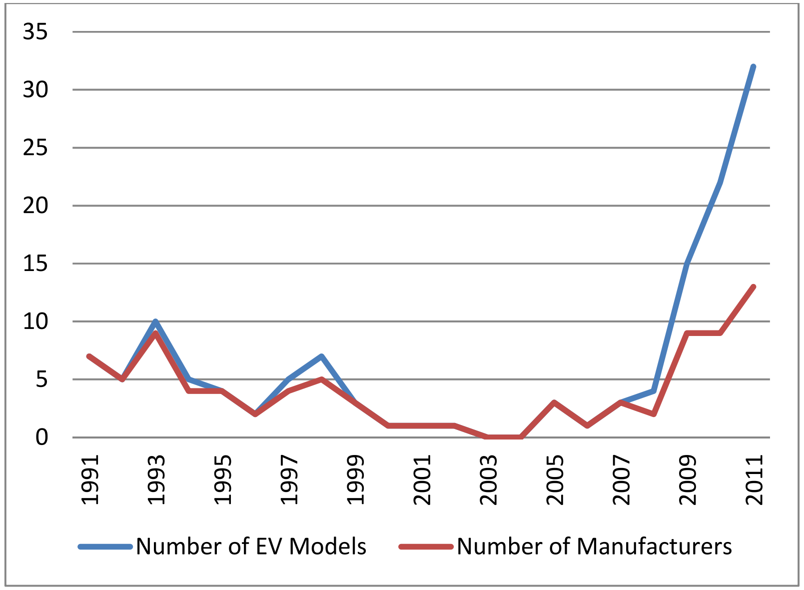

Figure 7: Electric vehicle models from 1991 – 2011.

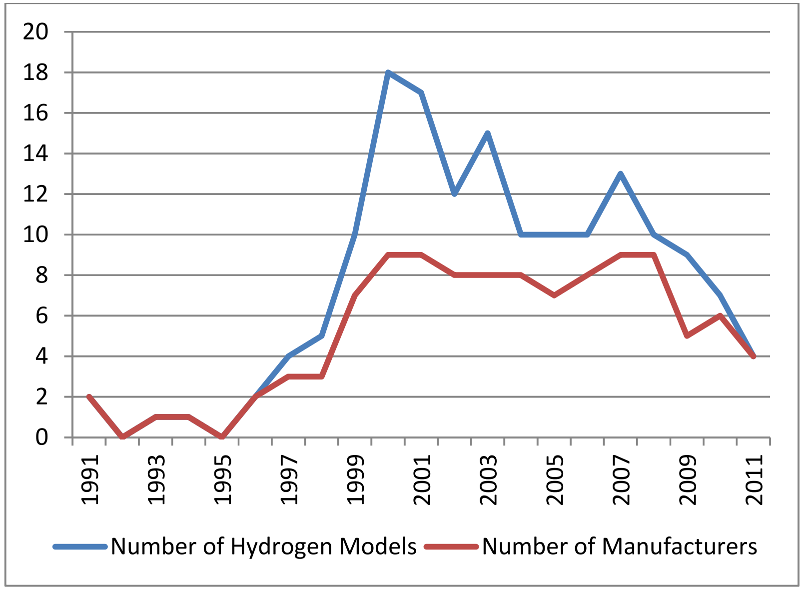

Figure 8: Hydrogen vehicle models from 1991 – 2011.

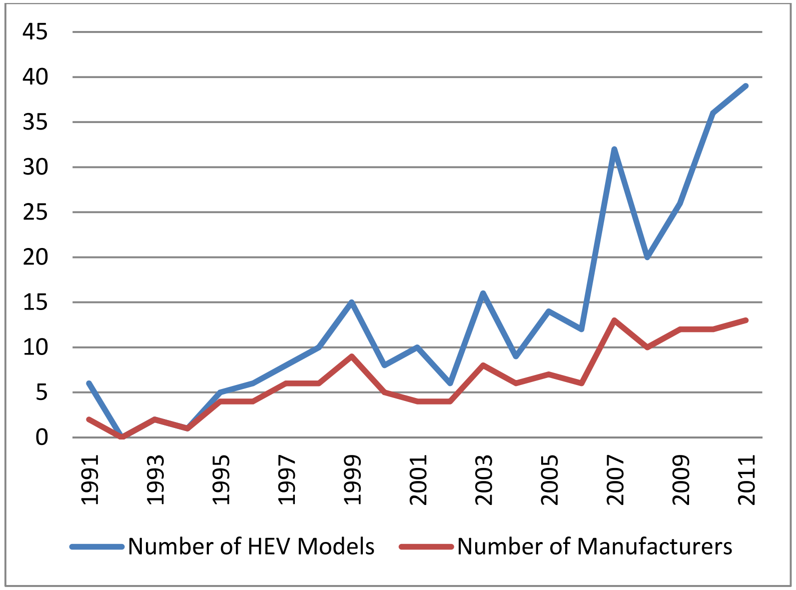

Figure 9: HEV models from 1991 – 2011.

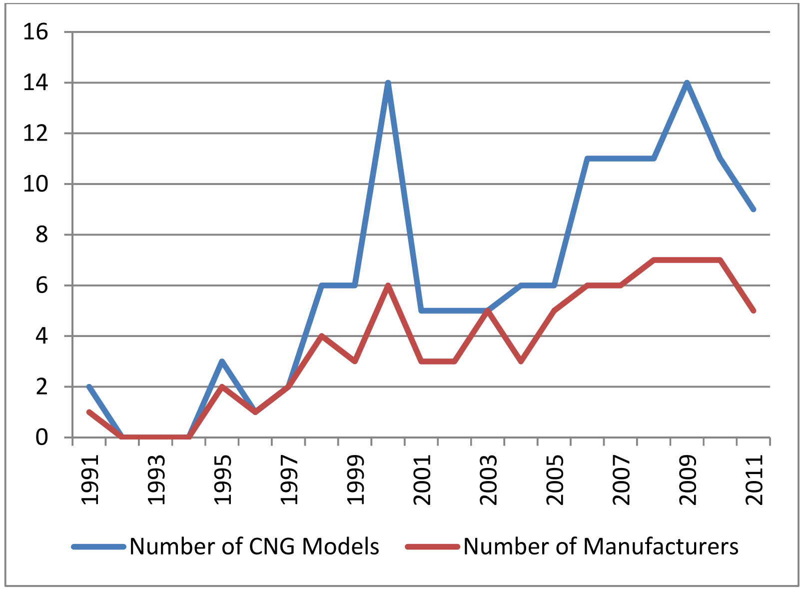

Figure 10: CNG models from 1991 – 2011

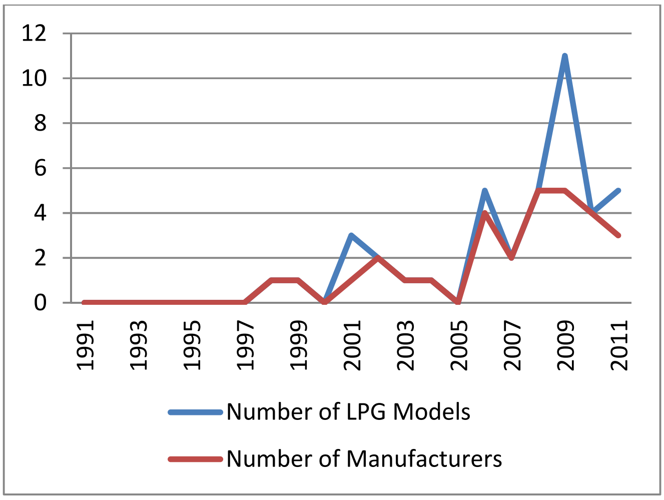

Figure11: LPG vehicle models from 1991 – 2011.

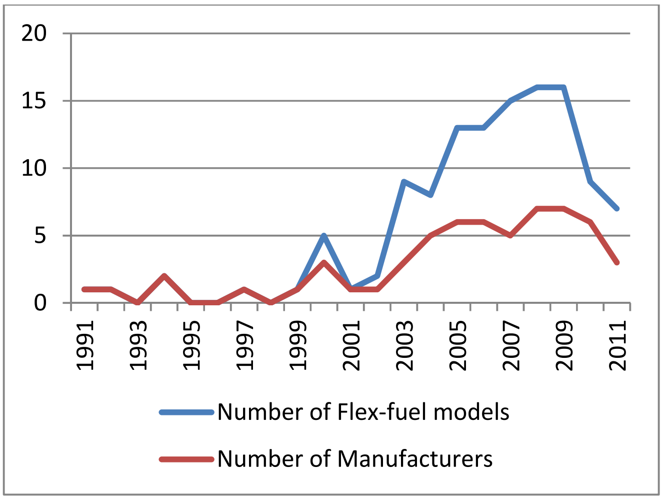

Figure 12: Flex-fuel models from 1991 – 2011.

In addition to the annual number of AFV models, figures 7 – 12 also show how many manufacturers presented those models. Within the individual AFV technologies, there appears 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 figure 12 (flex-fuel) from 1991 – 2001, figure 7 (EVs) from 1999 – 2007 and figure 8 (hydrogen) from 1991 – 1996. This period represents a situation where manufacturers are only making one model in a specific AFV technology. In the other period of development e.g. flex-fuel from 2003 – 2008 or HEV from 2007 – 2011 manufacturers make multiple models per 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 strategy.

5.3 Multi-fuel vehicles

	Petrol	Hydrogen	Flex-fuel	Electricity	CNG	LPG
Petrol	X	10	118	281	55	36
Hydrogen		X	2	99	1	0
Flex-fuel			X	6	3	1
Electricity				X	5	2
CNG					X	0
LPG						X

Table 4: Breakdown of multi-fuel vehicles by fuel combinations from 1991 – 2011.

For this study, a multi-fuel vehicle is any model that has two or more sources of fuel to power the vehicle. This includes a broad range of options from hybrid-electric vehicles that use petrol and electricity to hydrogen/petrol vehicles that have two separate fuel tanks. There are 619 AFV models in table 4, which represents 70% of all AFVs in this study. 80% of the multi-fuel models utilized petrol as one of the sources of fuel. This approach allowed manufacturers to experiment with different fuel options while still providing customers the reliability and familiarity of petrol. Petrol/electricity vehicles (HEV) were the most common combination of fuels in multi-fuel models followed by flex-fuel (petrol/ethanol) and hydrogen/electric. The prevalence of multi-fuel vehicles among AFV models makes it apparent that development of multi-fuel AFV models represents an important strategy for incumbents as they attempt to identify the technology or combination of technologies that will be commercially successful. It is important to note that table 4 represents an expanded notion of multi-fuel vehicles than that found in figures 5 and 6. The multi-fuel vehicles in figures 5 and 6 do not include any combination of petrol with another alternative fuel or hydrogen/electric vehicles.

5.4 Firm overview

Figure 13 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 in 2009 also developed the largest number of AFV models. Toyota, Volkswagen, Ford and General Motors were the four largest auto manufacturers by 2009 vehicle production and represent four of the five manufacturers that made the most AFV models. Mazda, Chana and BMW produced the least vehicles among the surveyed firms and also presented the fewest AFV models. A notable exception is Daimler, which was produced the 12th most vehicles in 2009, 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 and Brazil (where all three companies have a strong presence).

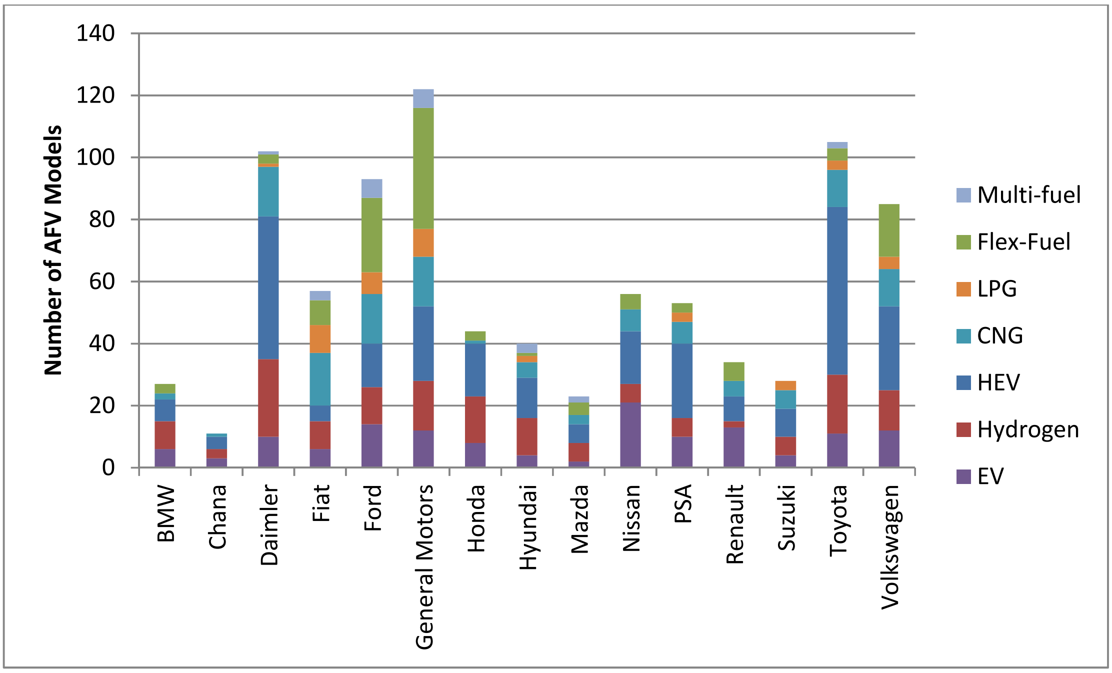

Figure 13: Number and type of AFV models developed by individual incumbent auto makers

5.4.1 Leaders and followers

During the study period, there were dramatic increases in the number of AFV models that used hydrogen, electricity or flex-fuel. For hydrogen vehicles this began in 1995, for flex-fuel vehicles 2002 and for EVs 2008. The companies that developed hydrogen vehicles models directly before this period 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 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) had 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. Over the study period, there was a broadening interest in HEV as a technology. This was evidenced by the increasing number of incumbents developing HEV models.

5.4.2 Eco-innovation overview

The theory section identified some of the differences between an eco-innovation and a "regular" innovation. These differences include eco-innovations incorporating environmental benefits into their value proposition, government support because they provide a social good and frequent miscalculation of their cost by consumers. However, firms need to develop and produce eco-innovations and consumers need to purchase them. Therefore eco and "regular" innovations still share many fundamental elements. The data collected in this study provides a way of comparing eco-innovations to "regular" innovations within the context of the product life cycle. During an era of ferment in the product life cycle, there is a *divergence* in technological diversity followed by the emergence of a dominant design and then *convergence* to that technology (Klepper, 1996). The results from this study show that incumbents have been diverging in the variety of alternative fuel powertrains they have been developing. Looking strictly at the increase in models that use different AFV technologies, eco-innovations appear to be following an important phase of the product life cycle. Suarez (2004) refers to this period as 'Phase III – creating the market'. According to the product life cycle, the next phase is emergence of a dominant design and a decrease in technological diversity. In Suarez's (2004) framework this is 'the decisive battle' and occurs after several firms have a large customer base. At that point, the mass market makes its decision as to which of the competing technologies will be successful. It remains to be seen whether a dominant design will emerge from the array of AFV powertrains, if the petrol-fueled ICE will remain dominant or if a new paradigm will develop where there is stable competition between different automobile technologies. This last scenario would be a marked difference from the typical product life cycle as described by Suarez (2004), Klepper (1996) and others.

6 Conclusion and discussion

This research set out to determine the strategies of incumbent automobile firms when multiple alternative fuel powertrain technologies are competing with the petrol-powered internal combustion engine. The results section shows that the largest 15 incumbent auto manufacturers have to a great extent developed incremental innovations (ICE-based AFVs) instead of more radical options such as hydrogen or pure electric vehicles. There has been a notable increase in the number of EV models since 2009, but the general trend over the study period was toward HEV, flex-fuel vehicles and other AFVs that also incorporate an ICE. 57% of the AFVs in this data set were able to use petrol as a fuel source.

Examples included bi-fuel vehicles where petrol was an independent fuel source and a hybrid approach that combined petrol with another alternative fuel e.g. HEVs and flex-fuel vehicles. Additionally, almost all of the AFVs in tables 1 and 2 that were produced or sold to consumers used petrol in some fashion. This wide-spread use of petrol gives an indication as to the strategies that manufacturers employ regarding AFV development. It is possible that in the future, automobiles will be powered exclusively by hydrogen, electricity or compressed natural gas. However in the near term, manufacturers will likely continue to incorporate petrol-fueled ICE engines in their AFV development strategy. Any shift toward vehicles that run exclusively on a fuel other than petrol will likely occur at a slow pace baring any remarkable technological advances or socio-economic developments.

A second conclusion that can be drawn from this research is that the total number of and powertrain diversity of AFV models from 1991 – 2011 has increased. This means that incumbents have not decided on the powertrain option that they believe will emerge as the technology of the future. When looking at these results from an industry, technology and firm perspective, the picture becomes more nuanced. On an industrial level, the number of AFVs, the number of firms developing AFV models and the diversity in powertrain technologies displayed uneven but positive growth throughout the study period. When looking at individual technologies, many AFV powertrains experienced waves of popularity at different times. The number of vehicle models that used hydrogen and flex-fuel exhibited a dramatic increase and decrease over a several year time span. As EVs are currently displaying a boom trend similar to that seen for flex-fuel and hydrogen models, it is difficult to know whether it will be followed by the same bust pattern that eventually occurred for the other two AFV technologies. Based on the data in this study, the only AFV technology to which the auto industry has really committed is hybrid-electric vehicles. The annual number of HEV models consistently increased during the study period as opposed to the more erratic gyrations from year to year that characterized other AFV technologies. From a firm perspective, incumbents have employed different strategies regarding AFV development. Some firms (e.g. VW and Ford) had a more balanced approach in that they developed several models in different powertrain categories while other firms (e.g. Toyota and Nissan) focused on specific technologies. The largest firms (with the exception of Daimler) had the greatest number of AFV models, and the firms that presented models with a specific alternative fuel powertrain early in the study period generally went on to have the largest number of models with that technology. An additional element of this research dealt with the performance of AFVs as an eco-innovation within the context of the product life cycle. AFVs have displayed the first three phase of the product life cycle as defined by Suarez which consists of an expansion of technological variety, working prototypes and early commercialization. Whether it continues to follow this process will depend on if a dominant design emerges and what happens to the different AFV powertrain technologies after this development.

Policy recommendations emerging from this research are based on the idea that the automobile industry is currently in a period of uncertainty and possibly an era of ferment. As such, the eventual technological outcome of this period cannot be known. Achieving a goal of sustainable transportation will likely involve a combination of incremental and radical powertrain innovations. As Christensen (1997) points out, incumbents seek the certainty of incremental innovations and prefer to devote resources to development of those technologies. Therefore, incumbent firms are likely to continue to develop powertrains such as flex-fuel, CNG, LPG and HEV technologies based on normal market dynamics. With that in mind, policies that provide funding for the development of incremental innovations are not the most efficient use of government resources. Push policies such as emission regulation should be used to encourage their development. Radical innovations such as hydrogen and electric vehicles are more risky and therefore require a different policy to approach to encourage incumbent firms to develop those technologies. Policy makers can encourage incumbents to develop radical innovations through push policies such as grants, low-interest loans and pull policies in the form of consumer subsidies and user convenience measures. Pilot projects which include cooperation between government agencies and firms are a good approach to identify niche markets for emerging technologies. These kinds of projects can be a useful way to stimulate individual technologies, but should be limited in their scope. In summary, we recommend a two-prong policy approach to encourage the move toward sustainable transportation. Policies such as emissions regulation should be used to drive incremental innovation while various funding instruments (consumer subsidies, low-interest loans, and grants) should be used to encourage the development of radical innovations. It is important to keep policies technologically agnostic so that the most competitive AFV powertrain succeeds. Hopefully this research provides policy makers a better understanding of the current situation of incumbent firm development of AFV technologies and these analyses can be used to inform policy decisions accordingly.

Areas for future research stemming from this analysis include a more in-depth look at the prototype and production model process. Understanding when and why incumbents develop prototype and production models would increase the explanatory nature of the research in this study.

Bibliography

Abernathy, W.,Utterback, J., 1978. Patterns of Industrial Innovation. Technology Review, 80, 41-47.

Ahuja, G. and Lampert, C., 2001. Entrepreneurship in the large corporation: A longitudinal study of how established firms create breakthrough discoveries. Strategic Management Journal, 22, 521-543.

Bakker, S., 2010. The car industry and the blow-out of the hydrogen hype. Energy Policy. 38, 6540-6544.

Bedsworth, L., and Taylor**,** M., 2007. Pushing Technology when it Pushes Back: Learning from California's Zero-Emission Vehicle Program. California Economic Policy Report, Public Policy Institute of California.

Blok, P., B. Van Wee, 1994. Het Verkeersvraagstuk, In: F. Dietz, W. Hafkamp, J. Van der Straaten (red.), Basisboek milieu-economie. Boom, Amsterdam/Meppel (In Dutch)

Chandy, R., and Tellis, G., 2000. The Incumbent's Curse? Incumbency, Size, and Radical Innovation. The Journal of Marketing, 64(3), 1-17.

Cleff, T., and Rennings, K., 1999. Determinants of environmental product and process innovation. European Environment, 9, 191-201.

Daimler, 2010. Technicity: Fuel Cell Future.

Daimler, 2011. The first fuel cell buses with hybrid technology are now in service in Hamburg [accessed 4-January-2012] http://media.daimler.com/dcmedia/0-921-657282-1-1417287-1-0-0-0-0-1-12759-614216-0-0-0-0-0-0-0.html?TS=1325717217998

Day, G., and Schoemaker, P., 2000. Avoiding the pitfalls of emerging technologies. California Management Review 42(2), 8-33.

E85prices, 2011. http://e85prices.com/ [accessed on 07-December-2011]

Ehrnberg, E., 1995. On the definition and measurement of technological discontinuities. Technovation. 15(7), 437-452.

Elektrisch Vervoer Centrum, 2011. [accessed 4-January-2012] http://elektrisch-vervoer-centrum.nl/

European Commission, 2009. Setting emission performance standards for new passenger cars as part of the community's integrated approach to reduce co2 emissions from light-duty vehicles. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0001:0015:EN:PDF [accessed on 06-December-2011]

French Embassy, 2011. "Bonus/Malus" – France encourages drivers to buy greener cars. http://www.ambafrnace-uk.org/bonus-malus-encourages.html [accessed 8-November-2011]

Goed bezig bus, 2012. 220XPRESS 100% Elektrisch. [accessed 4-January-2012] http://www.goedbezigbus.nl/fileadmin/user_upload/pdfs/Folder_elektrische_bussen.pdf

Hall, J., and Kerr, R., 2003. Innovation dynamics and environmental technologies: the emergence of fuel cell technology, Journal of Cleaner Production, 11, 459-471.

Hill, C., and Rothaermel, F., 2003. The Performance of Incumbent Firms in the Face of Radical Technological Innovation. Academy of Management Review 28(2), 257-274.

IEA, 2009. Outlook for hybrid and electric vehicles. OECD/IEA.Paris.

Jama (Japan Auto Manufacturers Association) 2011. Low-Emission Vehicle Shipments. http://www.jama-english.jp/statistics/low_emission/2009/101029.html [accessed 12-October-2011].

Jay, L., 1990. Green about the tills: markets discover the eco-consumer, Management review, 79, 24-29.

Jiang, L., Tan, J., and Thursby, M., 2010. Incumbent firm invention in emerging fields: evidence from the semiconductor industry. Strategic Management Journal, 32, 55-75.

Klepper, S., 1996. Entry, Exit, Growth and Innovation over the Product Life Cycle, The American Economic Review, 86(3), 562-583.

Metcalf, J., 1994. Evolutionary Economics and Technology Policy. The Economic Journal. 104 (425), 931-944.

Mom, G., 1997. Geschiedenis van de auto van morgen: cultuur en techniek van de elektrische auto. Kluwer Bedrijfsinformatie, Deventer.

Nissan, 2010. Amsterdam and Renault-Nissan Alliance Partner for a Zero-Emission Future. http://www.nissan-global.com/EN/NEWS/2010/_STORY/100922-01-e.html [accessed 4-November-2011].

OICA (International Organization of Motor Vehicle Manufacturers), 2009. World Motor Vehicle Production, Paris, 2010

Pohl, H., and Elmquist, M., 2010. Radical Innovation in a Small Firm: A Hybrid Electric Vehicle Development Project at Volvo Cars, R&D Management, 40(4), 372-382.

Reinganum, J., 1983. Uncertain innovation and the persistence of monopoly: Reply. American Economic Review, 73, 741-748.

Rennings, K., 2000. Redefining innovation – eco-innovation research and the contribution from ecological economics. Ecological Economics. 32, 319-332.

Rothaermel, F., 2001. Incumbent's advantage through exploiting complementary assets via interfirm cooperation. Strategic management Journal, 22, 687-699.

Suarez, F., 2004. Battles for technological dominance: an integrative framework, Research Policy, 33(2), 271-286.

Toyota, 2011. History of Toyota. http://www.toyota-global.com/company/history_of_toyota/ [accessed 4-November-2011].

Tokyo Motor Show, 2011 http://www.tokyo-motorshow.com/en/history/31.html [accessed 6-October-2011]

Transport for London, 2011. http://www.tfl.gov.uk/roadusers/congestioncharging/17094.aspx#Electric [accessed 4-November-2011].

US DoC, 1998. Partnership for a new Generation of Vehicles, Mobil Sources Technical Review Subcommittee.

US DoE, 2005. Hybrid Electric Vehicle Fleet Cost Calculator Tool.

US DoE, 2010. Vehicle Technologies Program. http://www1.eere.energy.gov/vehiclesandfuels/index.html [accessed 2-December-2011].

US DoE, 2011a. Alternative fuels and advanced fuels data center. http://www.afdc.energy.gov/afdc/data/vehicles.html [accessed 3-October-2011].

US DoE, 2011b. http://www.afdc.energy.gov/afdc/calc/ [accessed 4-November-2011].

US DoE, 2011c. Hybrid Electric Vehicle Basics http://www.afdc.energy.gov/afdc/vehicles/electric_basics_hev.html

US DoE, 2011d. Electric Vehicle High Occupancy Vehicle (HOV) Lane Exemption http://www.afdc.energy.gov/afdc/laws/law/MD/8382 [accessed 4-November-2011].

Utterback, J., and Abernathy, W., 1975. A Dynamic Model of Process and Product Innovation. Omega, 3(6), 639-656.

Van Bree, B., Vergong, G., and Kramer, G., 2010. A multi-level perspective on the introduction of hydrogen and battery-electric vehicles. Technological Forecasting & Social Change. 77, 529-540.

Van den Hoed, R., 2006. Sources of radical technological innovation: the emergence of fuel cell technology in the automotive industry, Journal of cleaner production, 15(11), 1014-1021.

Yu, A., Nascimento, P., Nigro, F., Frederick, B., Junior, A., Vieira, S., and Rocha, R., 2010. The Evolution of Flex-Fuel Technology in Brazil: The Bosch Case. Technology management for global economic growth 2010 proceedings.