

Development and Early Adoption of Electric Vehicles
Understanding the tempest

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Delft University of Technology

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Development and Early Adoption of Electric Vehicles

Understanding the tempest

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Preface

I am pleased to present this thesis as a result of my PhD research at the Delft University of Technology.

A quick reference to a no-less-venerable source than Wikipedia tells me that a preface “generally covers the story of how the book came into being . . . often followed by thanks and acknowledgments to people who were helpful to the author during the time of writing.” Well, here goes.

After following the lovely and talented Brynne DeNeen to the Netherlands in the winter of 2008, I worked for the better part of a year as a junior policy advisor at the Dutch social housing corporation WonenBregburg. Thereafter, I found myself in the seemingly enviable position of being a gentleman of leisure. However such a life did not suit me, and I quickly became restless, leading to a lengthy and remarkably unsuccessful job search. One kind gentleman at the Delft University of Technology offered to meet and talk about academic employment. Bert van Wee humored me by having the discussion in Dutch, and suggested I apply for an upcoming PhD opening looking at electric vehicles, specifically “The environment of early adopters from an innovations perspective”. To my (and many others) great relief, I was awarded the appointment, and thus began four years of academic wandering, dealing with the inevitable vagaries that accompany research in a new discipline.

The task of writing a PhD thesis entails mastering a substantial amount of material. I needed to obtain a firm grasp of the relevant theory, empirical literature, and research methods in an area in which I was decidedly unfamiliar – the development and early adoption of electric vehicles. Thankfully, for this task I had the help of my three intrepid advisors.

To Bert van Wee, Sjoerd Bakker, and Kees Maat, this thesis would not have been possible without your steadfast support and guidance. Bert, your thoughtful advice along with remarkably fast responses to e-mails has always kept me (more-or-less) properly focused during my study. Sjoerd, thank you for infusing this thesis with more than a touch of innovation studies while also greatly influencing my personal and professional interest in technological change. And to Kees, your focus on scientific rigor has given me an appreciation for how research should be properly done. In addition, your push for me to engage the literature, identify a worthwhile research question, and present my analysis in

clear manner has had a tremendous and positive impact on each of the studies in this volume. It has also led to my greater appreciation for science-based evidence and made me increasingly skeptical of arguments made in the popular media, a quality I hope many others share.

And finally, to my family and friends, it is impossible for me to express how thankful I am to have such wonderful people in my life. I love you all very much.

Will Sierzchula
Madison, December 2014

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1. Introduction

The storm is up, and all is on the hazard.

William Shakespeare

1.1. Uncertainty in the automotive sector

Due to factors such as climate change, dependence on unpredictable autocratic regimes for fuel, and depletion of finite oil resources, a vast transitional period in automobility could be underway. The drive to reduce the amount of oil that automobiles use and the greenhouse gases (GHG) that they give off has resulted in the creation of new technologies and implementation of stringent emissions regulation. Manufacturers have responded in a variety of ways including improving the efficiency of internal combustion engines and developing vehicles that use alternative fuels e.g., hydrogen and compressed natural gas (Yeh et al., 2007; Oltra and St. Jean, 2009; Yu et al., 2010; Bakker et al., 2012). In particular, electric vehicles (EVs) are seen as being one of the most promising innovations to reduce oil usage and GHG emissions from the transportation sector because they do not require gasoline/diesel for operation, there is a broad existing electricity infrastructure, and many firms have already commercialized production models (IEA, 2013). However, these activities have led to an increase in uncertainty regarding how the automobile industry will address oil and climate change issues, and more specifically the role of EVs therein. In order to provide insight into the situation, this thesis seeks to understand the dynamics which underpin EV development and market introduction.

Before discussing the specific research aim and question of this thesis, an overview is provided of topics that are relevant for the success or failure of EVs. This will help to understand gaps in the literature and consequently the PhD thesis's research aim and contribution. The following Section (1.2) describes the basic technical characteristics of EVs and compares them to other alternative fuel vehicles (AFVs) and an internal combustion vehicle (ICEV). Section 1.3 introduces the theoretical barriers that limit development and adoption of EVs. Section 1.4 identifies actors which play important roles during the emergence of EVs. Section 1.5 combines the technical characteristics, theoretical barriers, and important actors from the previous three sections in a brief literature review of the history of EVs from 1990-2010. Thereafter, Section 1.6 identifies the literature gap along with the

analyses that will address the associated research question. Finally, Section 1.7 addresses research scope, data, and methods.

1.2. Technical overview of electric vehicles

The technical characteristics of EVs provide a basis for understanding potential environmental gains and also the barriers that limit their development and wide-spread adoption. The following section provides an overview of additional important technological aspects including the battery, driving range, and refueling infrastructure. In addition, Table 1-1 also identifies how EVs relate to other AFVs by comparing the automobiles' basic features.

1.2.1. Vehicle emissions

While in many cases EVs produce fewer pollutants than ICEVs, this is dependent on several factors, primarily the source fuel of their electricity. When using an environmental life cycle assessment, EVs provide 10%-24% lower levels of GHG emissions (based on the present European electricity mix) than a comparable ICEV, although the precise ratio is dependent on the power grid mix, speed and load conditions, and vehicle lifetime in kilometers (Hawkins et al., 2012; Ma et al., 2012). In areas where electricity is primarily produced by coal plants (such as China), EVs emit on average 3.6 times as much hazardous particulate matter¹ than gas-powered ICEVs² (Shuguang et al., 2012). But since EVs do not necessarily use a carbon-based fuel, theoretically their pollution emissions would be extremely low if electricity comes from a clean source such as solar or wind. Operationally, this number can be zero, but some carbon would still be needed for production and disassembly. In addition, by not having tailpipe emissions, EVs provide localized environmental benefits through lower particulate matter levels, NO_x, and noise pollution (Shuguang et al., 2012). And as a country's energy production shifts from coal to nuclear, gas, and renewables, these environmental benefits become more pronounced.

1.2.2. Batteries, price, and range

Historically, EV powertrains have used a variety of different battery chemistries including Nickel Metal Hydride, Lithium-ion (Li-ion), Lead-Acid, and Sodium-Nickel-Chloride. Low-speed EVs³ generally use lead-acid batteries while EVs that are similar in size/speed to conventional automobiles use Li-ion batteries (ITAQ, 2008; Lowe et al., 2010). Due to their high cost per kilowatt hour (kWh), Li-ion batteries greatly influence both the purchase price and driving range of EVs. Most 'high-speed' EVs (which will be the focus of the majority of this thesis) cost between \$30,000 and \$40,000⁴, and have a 75-100 mile range e.g., Nissan Leaf, Ford Focus EV, and Honda Fit EV (Autotrader, 2013), although the \$70,000 Tesla Model S that goes 200 miles on a single charge⁵ (Tesla, 2013) does show how additional kWh's improve performance. As of the writing of this thesis (early 2014), no company had produced a mass market EV with a driving range equivalent to a comparable ICEV. This is likely because the vehicle cost would be so high that it would only be appealing to a niche market e.g. the Tesla Model S. Because battery costs display such a powerful influence in increasing vehicle prices, they are considered to be the most important factor limiting EV adoption (IEA, 2011; Wells and Nieuwenhuis, 2012). Improvements in battery prices have

¹ PM_{2.5}

² This is 2.5 times higher than diesel powered ICEVs.

³ These are small EVs with top speeds below 25 miles per hour.

⁴ In 2014 and not including federal/state rebates.

⁵ There are three battery options for the Tesla model S, 60kWh, 85 kWh, and 85 kWh performance. The example provided in the text refers to a vehicle with a 60 kWh battery.

progressed slowly even though auto manufacturers and power storage firms have been spending billions of dollars developing new technologies over the past several decades (Dijk et al., 2013). While some research expects that EV battery costs will dramatically decrease in the future, it is worth noting that such price reduction expectations have not been met in the past (Bedsworth and Taylor, 2007).

1.2.3. Charging and infrastructure

EVs require up to several (>10) hours from a 110 or 220 volt outlet or approximately 30 minutes using a fast charging station, dependent on battery size (Saxton, 2013). This represents a significantly longer period than the standard four minutes necessary to fuel an ICEV, contributing to a negative association of EVs by consumers. Furthermore, with fast charging there is the possibility that it might have a detrimental effect on a battery's energy density after repeated use (Boulanger et al., 2011).

Regarding the power grid, EVs represent both an opportunity to improve load balancing, but also the potential to intensify existing uneven energy demand cycles. The daily energy system load sees electricity demand ramp up between the hours of 5:00am and 8:00am, remain roughly level throughout the workday, peak between 4:00pm and 7:00pm, and then trail off. Such variety in usage entails a high capacity level, in accordance with peak demand, that is not utilized throughout much of the day (Lemoine et al., 2008). This is an inefficient setup which requires some power plants to rapidly increase their electricity output for a brief period while other times remaining underutilized (Dahl, 2004). In scenarios where battery recharge could be determined based on the system load, EVs could serve as buffers, allowing for fewer and more efficient utilization of power plants (Lemoine et al., 2008). An important concern is that EVs might further exacerbate the uneven load curve if a large number of operators recharge their batteries when the system load is at its highest. This scenario would require an even more dramatic expansion in energy capacity than necessary today, which would not be used for a majority of the day, resulting in an increase of electricity prices.

Another potential impact of EVs results from the synergy between their batteries and intermittent renewable energy sources such as solar and wind power. Combining these two technologies could lead to renewables contributing a greater proportion of daily energy use because issues associated with their intermittency would be decreased. Solar cells and wind turbines could power energy storage systems such as EV batteries, which would then provide electricity as needed (Anderson, 2006). EV batteries could also complement the existing fossil-fuel based energy system by traditional power sources not having to adjust their output throughout the day, resulting in power plants being more fully utilized and lower energy prices.

1.2.4. Comparison of EVs to other alternative fuel vehicles

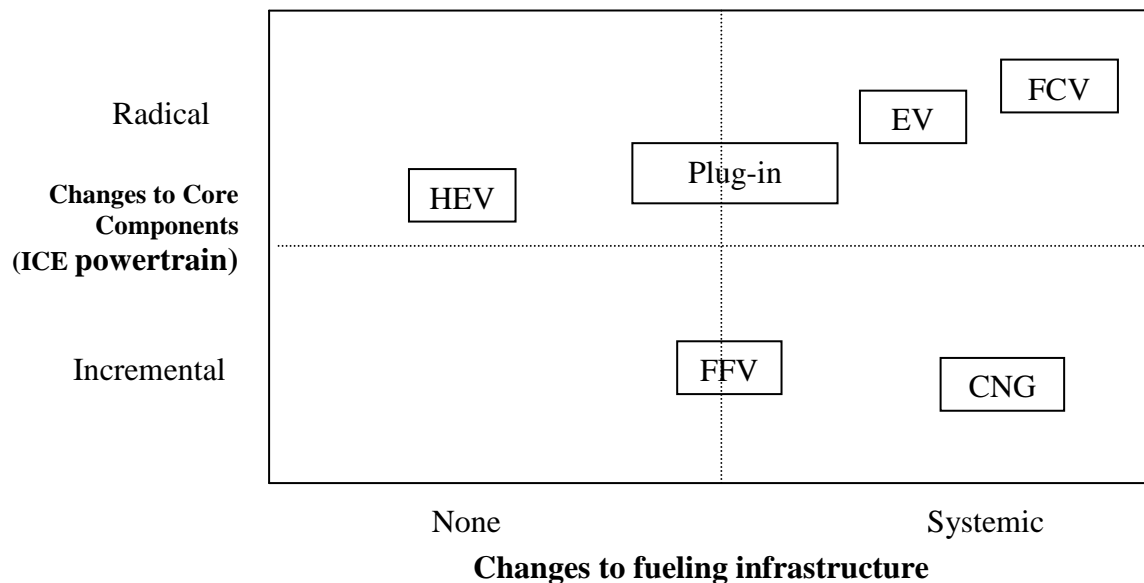
As identified in Section 1.1, there are several alternative fuels that have the potential to reduce GHG emissions in the transportation sector. However, pollution levels represent only one of several differences between these vehicles. Below in Table 1-1⁶ and Figure 1-1 are technical and performance characteristics of several AFVs with an ICEV provided for base line comparison.

⁶ Assumptions and references for Table 1 are provided in Appendix A.

Table 1-1⁷: Characteristics of midsize alternative fuel vehicles (based on US data⁸)

Vehicle	2012 price	Annual fuel costs	Fuel economy ⁹ (miles per gallon)	Fuel emissions (lbs. of CO ₂)	Range (miles)	Fueling time	Fueling stations
ICEV	\$16,500	\$1,416	26 city/36 hwy	9,605	372	4 min	121,000
EV	\$35,200	\$600	129 city/102 hwy	7,894	73	30 min	6,806
FCV	\$600/mo ¹⁰	\$898	61 city/61 hwy	3,792	240	4 min	10
CNGV	\$26,305	\$793	27 city/38 hwy	8,292	220	4 min	632
FFV	\$17,996	\$1,620	20 city/28 hwy	10,464	286	4 min	2,354
HEV	\$18,950	\$891	53 city/46 hwy	6,042	457	4 min	121,000

Because of their relatively new and complex powertrains, FCVs, HEVs, and EVs have higher purchase prices. However, due to features such as regenerative braking, they also have the best fuel economy which leads to lower annual fuel costs. CNGVs also do well in this category because natural gas is currently cheap relative to gasoline, although its prices have shown high levels of volatility over the past 10 years (EIA, 2013). When looking at annual fuel emissions, FCVs, HEVs, and EVs (the more technologically advanced powertrains) are the best performers. In both range and fueling time, EVs stand out as performing significantly worse than the other AFVs. To further explain differences between AFVs, Figure 1-1 provides a visual representation of how they compare technologically to the core ICEV powertrain components while also noting whether the automobiles require change in fueling infrastructure.

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

⁷ New acronyms from Table 1-1: FCV = hydrogen fuel cell vehicle, FFV = flex-fuel vehicle (uses ethanol), and HEV = hybrid-electric vehicle

⁸ Data from the US as opposed to the EU was used for two reasons. Firstly, FCVs are not available for purchase/lease in the EU. Secondly, the number of fueling stations is not readily available for many EU countries.

⁹ A version of this data with kilometers instead of miles is available in Appendix B.

¹⁰ The Honda FCX Clarity is currently only available for lease, so a purchase price comparison is not possible.

Some powertrains such as the FFV and CNGV still use an internal combustion engine, while others (HEV, EV, and FCV) represent a radical change to this core component through the use of batteries, electric motors, or fuel cells. In addition, AFVs also vary according to how they relate to the fueling infrastructure. For instance, the hybrid-electric powertrain runs on gasoline, so it does not require change in the current fueling system. Others AFVs including EVs and FCVs require the installation of new fueling stations. Still others such as the plug-in HEV and FFV can use existing infrastructure, but could also run on a new fuel (electricity and ethanol respectively). Regarding how Figure 1-1 relates to the development and adoption of AFVs, commercialization of an innovation becomes more difficult and expensive moving from bottom to up and left to right i.e., there are greater barriers to the introduction of FCVs than HCVs. This is a topic that will receive more attention in the subsequent section.

1.3. Theoretical factors limiting the development and adoption of EVs

Innovation literature identifies several important theoretical concepts that are particularly relevant and influential to the emergence of EVs. These include the difficulty in transitioning from a locked-in dominant design and fundamental dynamics resisting the emergence of technology such as EVs, a radical eco-innovation¹¹ that requires a change in infrastructure and consumer behavior. These factors are detailed below.

1.3.1. Lock-in of a dominant design

Since the rise of ICEVs as the dominant automobile design almost 100 years ago, industrial dynamics have functioned to lock-in the technology as an integral part of society's fabric, consequently erecting barriers that limit the development and adoption of competing innovations. Positive feedback through mechanisms such as learning-by-doing, economies of scale, and network externalities can serve to focus technological development along a particular path or trajectory (Dosi, 1982; van den Bergh et al., 2006). In the case of ICEVs, this has led to steady improvements in several areas including fuel efficiency, performance, safety, and comfort (Abernathy and Utterback, 1978). In addition to such incremental improvements, many dominant designs experience a buildup of supporting elements as other industries develop complementary products and services (Arthur, 1989). During the past 100 years, ICEVs have become entrenched in the fabric of everyday life through factors such as improvements in engines, expansion of fueling stations, the creation of automobile standards, and the rise of inter-industry network dependencies (Unruh, 2000). Consequently, a very strong system or what Geels (2002) refers to as a socio-technical regime has developed around the ICEV. When a technology such as the ICEV becomes dominant through technological and institutional positive feedback mechanisms, it is referred to as lock-in (Arthur, 1989). Unlocking such dominant technologies is a difficult and lengthy affair (Unruh, 2002), requiring an emerging innovation, larger macro-level changes e.g. the rise of environmentalism, and a destabilization of the existing socio-technical regime (Geels and Schot, 2007). The EV is one radical innovation that challenges the locked-in paradigm of ICEV and gasoline/diesel fuel.

1.3.2. Emergence of a radical innovation

Innovations vary in their relationship to the incumbent technology. There is a sharp distinction between those that are based on existing knowledge (incremental) and those that

¹¹ Following Rennings (2000), this thesis uses a broad definition of eco-innovations as the new concepts, behavior, products, and processes, which assist in the reduction of environmental impacts or the attainment of specified ecological sustainability goals. This thesis will be mostly dealing with eco-innovations as products.

require a new source of expertise (radical) (Anderson and Tushman, 1990). In that regard, EVs represent a radical innovation because they use a high-energy battery and electric motor instead of an internal combustion engine. According to Tushman and Anderson (1986), “Major technical change opens new worlds for a product class but requires niche occupants to deal with a considerable amount of ambiguity and uncertainty as they struggle to comprehend and master both the new technology and the new competitive environment” (pg. 460). This uncertainty emerges because the extent that an innovation differs from the dominant design has an increasingly negative effect on a broad array of industrial dynamics including consumer willingness to pay, future profitability of a technology, and government involvement (Arrow, 1962; Nelson and Winter, 1977; Anderson and Tushman, 1990). And while the empirical data analyzing actions under uncertainty is “messy” (Dosi and Egidi, 1991), the theory holds that such ambiguity is a disincentive to innovation (Jaffe et al., 2005). Therefore, the radical nature of EVs increases related uncertainty and inherently acts as an obstacle to their development. Furthermore, following previous radical technologies (Adner, 2002), EVs compare poorly to ICEVs based on many traditional cost and performance metrics e.g., driving range and purchase price (see Table 1-1).

1.3.3. Lack of charging infrastructure

EV adoption faces another barrier in the lack of charging infrastructure, which is exacerbated due to the automobile’s limited driving range. Expectations regarding automobile use are based on the current paradigm where vehicles have ~375 mile (600 km) range with widely available refueling infrastructure (Egbue and Long, 2012). And while the number of charging stations has increased markedly (IEA, 2013), infrastructure shortage is still identified by consumers, auto manufacturers, and local public officials as one of the biggest challenges to wide-spread EV adoption (Egbue and Long, 2012; Zubaryeva et al., 2012). Limited charging infrastructure is often dubbed the *chicken or egg* problem. Consumers do not want to purchase an EV without ample available charging stations, and organizations (public and private) do not want to invest in building such infrastructure until there is a sufficiently large market (Struben and Sterman, 2008). The IEA (2013) has found national investment in charging infrastructure to be meager, especially in comparison with R&D and consumer subsidies. Financing for charging infrastructure has been identified as “perhaps the most urgent need in all EV markets” (IEA, 2013 pg. 27). As such, widespread EV adoption will require significant expansion in support infrastructure e.g., maintenance shops and charging stations in addition to appealing automobiles (Tran et al., 2013).

1.3.4. Consumer bounded rationality

Rogers (1995) noted that innovation diffusion is “an uncertainty-reduction process” (p. 232), where consumers use information about a technology when they make an adoption decision. However, this process is constrained because it is not possible for someone to have perfect information about a situation (Kahneman et al., 1986). Instead of using optimal decision making to maximize one’s utility, individuals seek only an acceptable option (Simon, 1956) because they have merely a portion of all available information (a situation referred to as bounded rationality). Consequently, the adoption of innovations is a haphazard process where the best option does not always succeed (Dosi and Nelson, 1994). Consumer bounded rationality affects EV adoption in two important ways; it often leads to misestimating lifetime ownership costs and reduces consumer willingness to pay.

In place of calculating out the total cost of ownership of a product, consumers often rely on heuristics or rules of thumb to guide their purchasing behavior (Jaffe and Stavins, 1994;

Schleich, 2009). This can lead an individual to place too much emphasis on the initial cost and not accurately value operating expenses (Levine et al., 1995). Specifically regarding EVs, consumers looking to purchase alternative fuel vehicles do not accurately incorporate fuel economy in their vehicle purchase decisions, which can lead them to buy automobiles that have a higher total life cost (Turrentine and Kurani, 2007). For these reasons, innovations that have high purchase prices and low operating expenses (such as EVs) often experience reduced rates of diffusion (Brown, 2001; Jaffe et al., 2005).

Due to limited consumer experience with EVs (by virtue of it being a new technology), information about its operation, performance, and reliability is neither well-known nor widespread (Dyerson and Pilkington, 2005; IEA, 2013). Consumer understanding of EVs is also affected by their radical differences in relation to the dominant ICEV technology. Increased uncertainty resulting from both of these factors ultimately leads to a decrease in the amount that consumers are willing to pay for EVs and consequently lower adoption rates (Arrow, 1962). One general expectation is that as consumer experience with EVs increases, then the general public's bounded rationality regarding the innovation will go down (Mueller and Haan, 2009), increasing the likelihood that consumers will buy the automobiles. However to get to that point, it is necessary to encourage a sufficient number of early adopters to keep the market viable (Egbue and Long, 2012).

1.3.5. Eco-innovation and a pollution externality

EVs are an eco-innovation because they provide reduced environmental effects relative to gasoline or diesel fueled ICEVs, as evidenced by their lower CO₂ emissions in Table 1-1. Besides helping address the environmental concerns identified in the Section 1.1, lower pollution levels also provide economic benefits such as decreased healthcare costs and fewer sick days from work as well as social benefits through improved population health and increased quality of life. However, EV adoption rates are limited because lower pollution levels are not included in the price that consumers pay. This results in pollution being an externality (a cost or benefit imposed on a third party) which can lead to market failure (the improper allocation of goods and services). As a result of this pollution externality, manufacturers are disinclined to invest in EV development because they are not compensated for all of the gains that the technology provides. In addition, environmental issues such as climate change entail such tremendous uncertainty through potential impacts and policy responses that manufacturers are disincentivized more so than normal from developing eco-innovations (Jaffe et al., 2005). According to environmental economics, public policy should be used to correct for market failure arising from pollution (Rennings, 2000).

1.4. Actors

In order to address innovation barriers such as those identified above, a broad array of actors are necessary to support both technology push (development) and demand pull (market creation) dynamics (Mowery and Rosenberg, 1979). In the case of EVs, the most important actors are auto manufactures and consumers, respectively. However, because EVs are an eco-innovation, governments also have a role to help correct for market failure arising from pollution. Furthermore, governments will also be involved because they install infrastructure such as the charging stations needed for broad EV adoption (Bakker and Trip, 2013; Egbue and Long, 2012). The roles of these three actors along with the barriers that they address are highlighted below in Table 1-2 and more specifically described in the following subsections.

Table 1-2: Role of actors relative to barriers to the development and adoption of EVs

Actor	Role	Barrier(s) addressed			
		Radical technology	Infrastructure	Bounded rationality	Pollution externality
Government	Address market failures	X	X		X
Auto industry	Develop EVs	X	X		
Consumers	Provide feedback on EVs	X		X	

1.4.1. Automotive industry

In order to commercialize an EV, auto manufacturers need to acquire the necessary expertise, create a functional prototype, and then develop the production model. This is an expensive, long, and non-linear process that involves multi-directional interactions between the different innovation phases through dynamics such as learning, feedback loops, and lock-in effects (Kline and Rosenberg, 1986). The market introduction of an EV is complicated by an increase in uncertainty associated with the emergence of a radical technology (Sahal, 1981; Anderson and Tushman, 1990; Tran et al., 2013). A part of this uncertainty comes from the need for new expertise in charging, electric motors, and batteries, which are required to develop EVs. Because auto manufacturers do not have this knowledge in-house, they are frequently looking to collaborate with external organizations (Dyerson and Pilkington, 2005), which adds additional complexity to the innovation process (Powell et al., 1996).

And while EVs compare poorly to ICEVs in many cost and performance metrics, they also could have a steep improvement curve such as that seen with other radical innovations e.g., steam engines, digital storage, and personal computers (Foster, 1986; Christensen, 1997). In such a case, it is possible that battery improvements could lead to dramatic reductions in price and significant improvements in driving range such that EVs enjoy competitive advantages relative to ICEVs. Consequently, auto manufacturers may feel compelled to develop EVs because of the desire not to be left behind in the event that EVs comprise an increasing proportion of the automobile market (Dyerson and Pilkington, 2005), but related uncertainties act as a limitation on their investment in this technology.

1.4.2. Government

The primary role of public policy relative to EVs is to correct for market failure that arises from the externality pollution. As innovation policy can never be technology neutral, it always ends up favoring one particular design or another (Azar and Sandén, 2011). Thus, there is the concern that innovation policy could distort the market and ‘pick a winner’ which ends up being technologically inferior e.g., Solyndra.¹² This worry is particularly pressing for alternative fuel vehicles because there are multiple competing technologies (FFVs, EVs, CNGVs, and FCVs), and support for the wrong one may lead to lock-in of an inferior technology such as that found with the QWERTY keyboard.¹³ In addition, the uncertainty identified above influences public policy in that it leads to policy makers having only vague notions of how an innovation’s price and performance will progress over time. Therefore, governments do not know whether support of alternative fuel vehicles, new transportation

¹² A US solar company that received more than \$500 million in federal loan guarantees in 2009 before going bankrupt in 2011.

¹³ The QWERTY keyboard is the classic innovation example where a product with superior performance (The Dvorak keyboard) lost commercially to an inferior technology.

modes, or efficiencies in the existing technology will be most effective in decreasing GHG emissions from the transportation sector.

Economically, taxes are the best way to correct market failures that arise from externalities such as pollution; however, they are often politically untenable (Kennedy et al., 1994; Harrington et al., 2001). So, governments have resorted to a combination of policy instruments including R&D grants to auto manufacturers, emissions standards, consumer subsidies, and charging infrastructure installation in order to support EV development and adoption (Collantes and Sperling, 2008; US DoE, 2010; ACEA, 2012a; ACEA, 2012b).

A secondary role for the government is to help establish enough charging infrastructure to support wide-spread EV adoption (Tran et al., 2013). Fuel providers are hesitant to install charging stations because of the low number of EVs, and most consumers are reluctant to purchase the automobiles due to the lack of infrastructure (Struben and Sterman, 2008; Caulfield et al., 2010). Some argue that incentives or public-private partnerships are necessary to overcome this *chicken or egg* problem (Farrell et al., 2003). Consequently, national governments, along with some private firms and local municipalities have been investing in developing charging infrastructure to help set the stage for broader EV use (Bakker and Trip, 2013; IEA, 2013).

1.4.3. Consumers

EV price and functional capabilities have a direct influence on consumer attitudes about the innovation (Struben and Sterman, 2008; Egbue and Long, 2012). In addition to high purchase costs, consumer concerns are widespread and include a fear of being unable to find a charge station (Steinhilber et al., 2013), the long charging time (Hidrue et al., 2011; Neubauer et al., 2012), and poor performance relative to ICEVs (Lane and Potter, 2007; Hidrue et al., 2011). Furthermore, uncertainty surrounding the commercialization of EVs lowers the amount that consumers are willing to pay relative to the conventional ICEV. All of these factors results in a low number of potential EV buyers and in effect reduces their expected adoption rate (Arrow, 1962; Sovacool and Hirsh, 2009).

On the flip side, there are EV performance characteristics that make the automobiles more appealing to consumers, specifically their (potentially) low pollution emissions and the ability to achieve full torque immediately when the accelerator is depressed. As a result, EV increased acceleration capabilities have led to the development of niche markets (sports cars and eco-consumers) in which these characteristics are valued (Lane and Potter, 2007; van Bree et al., 2010). However, studies into consumer preferences show there is only a small percent of buyers that are willing to pay a premium for EVs even though they may be environmentally friendly, sporty, or innovative (Lane and Potter, 2007; Hidrue et al., 2011).

1.5. EVs 1990-2010: an abbreviated review

The technical characteristics of EVs, theoretical barriers to their market introduction, and important actors coalesced during the 1990-2010 timeframe as firms sought develop and commercialize the automobiles. Through analysis of that period, this section uses available scientific research to identify important overarching factors that have historically and continue to influence the emergence of EVs.

1.5.1. Meaningful impact

The introduction of GM's electric concept *Impact* in the 1990 Los Angeles Auto Show and subsequent announcement that the automobile would be brought to production ushered in two dramatic decades for electric vehicle development and production (Bedsworth and Taylor, 2007; Dijk et al., 2013). This time saw periods of heavy commercialization activity, notably one in the 1990s and the other in late 2000s along with intermittent attention from both auto manufacturers and policy makers. However, the vast majority of consumers have estimated EVs to be unappealing mainly due to their high costs and limited performance capabilities, resulting in a failed commercial attempt in the 1990s, and a significant barrier to their introduction in the late 2000s (Dijk and Yarime, 2010; IEA, 2013).

Governments have introduced a wide range of policies to encourage EVs diffusion. Notably, the California Air Resource Board's low emissions vehicle program in 1990 mandated the sale of zero emissions vehicles later in that decade (Collantes and Sperling, 2008). However, that US state was not alone; countries around the world have implemented supportive policies. European nations encouraged the introduction of EVs largely through R&D programs and pilot projects. For example, almost 400 EVs were employed through a demonstration effort in the Swiss town Mendriso, and 2,000 of the automobiles were the target of an extensive field test in the French city La Rochelle (Hoogma, 2002). The Japanese Ministry of International Trade and Industry issued an aggressive market expansion policy in 1991, followed by a series of pilot projects throughout the 1990s (JEVA, 2000). These programs had the goal of putting hundreds of thousands of EVs on the road by the 2000s (MITI, 1990; Bedsworth and Taylor, 2007; Hoogma, 2002).

During this period, incumbent auto manufacturers invested tremendous resources in developing EVs, and produced several prototype models including Ford's Ecostar, Honda's EVX, BMW's e1, and the Nissan FEV-I (Mom, 1997). Only a few of these prototypes were ever introduced to the market as production models, notably GM's EV1 and Toyota's RAV4EV, and by the early 2000s, manufacture of EVs had practically stopped (Dijk et al., 2013). These automobiles suffered from the same barriers to adoption as the current wave of EVs (high purchase price, low driving range, and little charging infrastructure). Although their situation was exacerbated because they were using lower energy density battery technology (lead-acid or nickel based), resulting in even lower driving ranges. Primarily due to production costs, EVs were determined not to represent a viable business model; pilot projects ended, supportive policies were severely watered down, and auto makers gradually retreated from the EV market in the early 2000s (Patchell, 1999; Funk and Rabl, 1999; Dijk and Yarime, 2010).

1.5.2. Retrenchment and re-emergence

After interest in EVs died down, focus shifted to different low-emissions vehicle powertrains including HEVs and FCVs (Dijk and Yarime, 2010; Bakker et al., 2012b). Governments specifically supported these AFVs through policies such as FreedomCAR in the US and the Clean Energy Vehicles Introduction Program in Japan. Auto manufacturers also devoted resources toward developing expertise in those powertrains (Oltra and St. Jean, 2009). And while the HEV can be seen as a commercial success (Dijk and Yarime, 2010), FCVs failed to live up to expectations, following EVs into disappointment along Gartner's technology hype cycle (Bakker, 2010).

Convergence of a series of factors including more stringent fuel emissions legislation, supportive R&D policies, improvement in battery technology, and higher fuel prices

contributed to the re-emergence of EVs in the late 2000s. The wide-scale commercialization of the Nissan LEAF and Mitsubishi iMiEV in 2009 along with the appearance of startup manufacturers such as Coda and Tesla indicated a level of momentum behind the most recent introduction of EVs. And while there is disagreement about its future success prospects (Dijk et al., 2013; Wells and Nieuwenhuis, 2012), EVs have reached a level of commercialization much greater than that found in the earlier 1990's attempt. However, a general conclusion about this development is that any sort of broad EV diffusion in the future will still require supportive governmental policy, industrial buy-in, and changes in consumer behavior (van Bree et al., 2010; Tran et al., 2013; Dijk et al., 2013). In one positive sign, recent market introductions indicate that large auto makers now view the EV market as a commercial opportunity instead of a regulatory requirement (Magnusson and Berggren, 2011), specifically in niche markets such as sports cars and low emissions vehicles (van Bree et al., 2010). And while auto manufacturers have a diverse patent portfolio of automotive technologies e.g., FCVs, and HEVs (Oltra and St. Jean, 2009), the firms are beginning to show more of a preferential attitude toward EVs (Schwedde et al., 2012).

Increasingly stringent environmental policies, notably the 2009 US fuel economy standards and 2009 EU vehicle emission regulations, have affected EV commercialization in two important ways. Firstly, they encourage auto makers to sell EVs since it helps them meet regulatory requirements. Conversely, they reduce EV operational advantages because they result in lower ICEV fuel costs. However, improved fuel economy and lower emissions could come through increased manufacturing costs and subsequently a higher purchase price, causing an improvement in the EV/ICEV value proposition. Thus, EVs will have to contend with ICEVs that are steadily improving in their operational costs. This dynamic is often present when a radical technology offers a new price/performance frontier and functions to slow adoption rates (Geels, 2002).

1.5.3. Summary of this period

Based on studies during the 1990-2010 timeframe, EV adoption is seen as being very limited without stimulation from external factors such as stringent emissions regulations, rising fuel prices, or financial incentives (Eppstein et al., 2011; Shafei et al., 2012; Tran et al., 2013). Of those factors, consumer subsidies in particular are expected to be necessary for EVs to reach a mass market (Hidrué et al., 2011; Eppstein et al., 2011). Subsequently, governments around the world have implemented this demand-pull instrument through different types of financial incentives (IEA, 2011; IEA, 2013). Countervailing forces include consumer uncertainty regarding new technological components and operation as well as the gradual improvement in ICEV fuel efficiency. If consumer confidence in a technology is lacking, then financial incentives will not be very effective in stimulating EV diffusion (Egbue and Long, 2012). A common conclusion that policy makers, researchers, and auto manufacturers draw about the current prospects for EV commercialization is that they are uncertain what the future of the innovation will be (Egbue and Long, 2012; Tran, 2013; IEA, 2013).

1.6. Research gap and question

The above section gives a literature overview which explains the current understanding of factors which influence the development and commercialization of EVs. Building on that foundation, this section of the thesis identifies a hole within the literature and an associated research question used to bridge this gap, providing a better grasp of important dynamics that impact the emergence of EVs.

There is the concern that the existing EV literature may not accurately reflect the current industrial environment because most studies analyzed stated as opposed to observed consumer behavior, or were conducted before the most recent commercialization of the automobiles. Due to the value-action gap, stated preference surveys may not correctly identify consumer behavior regarding EVs. As a result, there are reasons to doubt whether studies using such surveys correctly reflect consumer attitudes toward EVs (Homer and Kahle, 1998; Lane and Potter, 2007). And while the influence of government policies on consumer adoption of EVs has been studied with agent based modeling (Epstein et al., 2011; Shafei et al., 2012), that does not provide the sort of insight or certainty that comes from empirical analysis, which is now possible that the automobiles have been available for purchase for several years. In addition, because industrial dynamics change so quickly during the emergence of a radical innovation (Tushman and Anderson, 1986; Klepper, 1996), studies focusing on manufacturer activities either need to be updated (Oltra and St. Jean, 2009), or expanded to look at a broader set of firms (Magnusson and Berggren, 2011).

The primary research gap which this thesis seeks to fill is the lack of knowledge regarding recent efforts of the automotive industry to develop and commercialize EVs. While earlier studies focused on the R&D stage of EV development, the innovation has moved on to the commercialization phase, identifying the need for an updated understanding of the industrial dynamics at work. And because EVs have been broadly available for purchase for a number of years, it is now possible to empirically analyze important factors such as prototype and production model development, alliance formation, and vehicle sales. As such, the central research question of this thesis is:

How has the automotive industry approached the development and commercialization of electric vehicles?

To answer that question, this thesis uses a series of sub-queries which each occupy a single chapter of this thesis. Figure 1-2 below shows how these chapters are positioned relative to one another and the broader EV industry, while the following subsections describes the analysis that was conducted for each chapter.

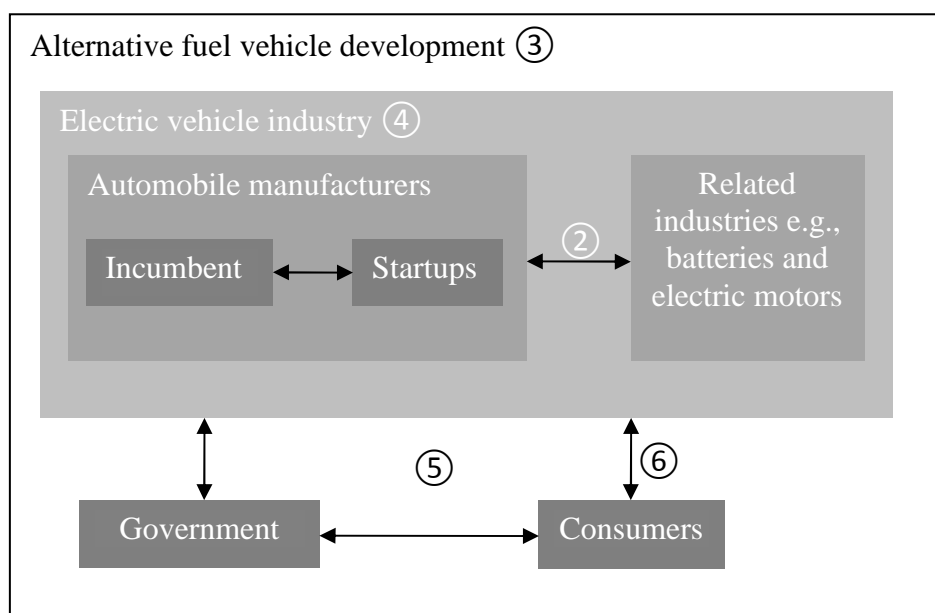


Figure 1-2: Thesis chapter positioning within the broader EV industry

1.6.1. Knowledge creation

As one of the characteristics of radical technical change is that new innovations require expertise outside that necessary for the conventional technology (Anderson and Tushman, 1990), auto firms have been rapidly trying to accumulate knowledge in fields such as batteries and electric motors (Dyerson and Pilkington, 2005; Magnusson and Berggren, 2011). Based on patent research, auto manufacturers have been actively developing their own knowledge regarding those key electric vehicle technologies (Oltra and St. Jean, 2009; Wesseling et al., 2013). However, the increased complexity of technologies means that firms are often no longer able to develop radical innovations on their own. Powell et al. (1996) have determined that the locus of innovation has shifted away from individual firms and toward networks of organizations. Therefore, to understand how auto manufacturers are acquiring the expertise necessary to develop EVs, it is important to analyze the collaborations they are making in key knowledge areas. The primary research question for Chapter 2 is *how have auto manufacturers approached the acquisition of knowledge from disparate industries in order to produce a commercial electric vehicle?*

1.6.2. Alternative fuel vehicle introduction

Within the broader auto industry, manufacturers have commercialized (or are attempting to commercialize) many alternative fuel powertrains including hydrogen fuel cells, hybrid-electric, purely electric, and engines that can run on CNG and biofuel (Oltra and St. Jean, 2009; Dijk and Yarime, 2010; Yu et al., 2010; Bakker et al., 2012). These alternative fuel vehicles provide different technological approaches for lowering emissions in the transportation sector. To understand the early adoption environment of EVs, it is necessary to see how that particular powertrain fits into a broader market for alternative fuel vehicles. The primary research question for the third chapter is, *how have incumbent auto firms approached the development of electric automobiles relative to other alternative fuel vehicles?*

1.6.3. The emerging electric vehicle market

There are several different dynamics which indicate that a radical technological shift could be underway in an industry including an increase in technological variety, more startups, and heightened uncertainty (van Dijk, 2000; Klepper, 1996). While Chapter 3 gives a broad overview of the development of alternative fuel technologies, it does not provide much detail for what is happening specifically in the EV market. A more in-depth analysis into that area is supplied in Chapter 4 which looks at the important industrial dynamics of technological variety and startup vs. incumbent firm behavior. The primary research question for this section is, *to what extent did incumbent and startup firms develop a variety of different electric vehicle types based on performance criteria?*

1.6.4. Consumer financial incentives and EV adoption

In general, governments are using broad emissions regulation to gradually improve the environmental impact of vehicles, while being more selective over their use of technology-specific policies. Uncertainty about the EV industry has made it difficult for policy makers to determine if and how to support the technology (Struben and Sterman, 2008; van Bree et al., 2010; Tran et al., 2013). There are several policy measures available including consumer financial incentives, infrastructure development, producer subsidies/loans, and emissions regulation. Historically, these measures have had a mixed success rate e.g., HEV adoption, loan recipients Tesla and Solyndra, and ZEV/CAFE regulation (Bedsworth and Taylor, 2007; Diamond, 2009; Gallagher and Muehlegger, 2011). Because EVs have only been widely

available since approximately 2010, there is little data to know how the policies that are in place have fared. Consequently, much of the research looking into the effectiveness of EV policies has relied on surveys from the general public (not from adopters) (Eppstein et al., 2011; Egbue and Long, 2012; Hidrue et al., 2011). However, because of a phenomenon known as the ‘value-action gap’ there is the concern that information from consumer surveys may have little relation to the purchase of cleaner vehicles (Lane and Potter, 2007). As such, governments are implementing policies without a clear understanding of their effectiveness. The fifth chapter of this thesis focuses on the relationship between financial incentives and EV adoption to help note how governments could help stimulate diffusion of the innovation. Here the research question is *to what extent do consumer financial incentives and other socio-economic factors explain national EV adoption rates?*

1.6.5. Fleet manager adoption of EVs

Consumers often reject new technologies and instead rely on a notion of tradition or familiarity when considering products, especially for hardware (such as an automobile) that has high capital costs (Rogers, 1995; Kirsch, 2000). Because the current commercialized EVs have only been on the market for a few short years, there is little available data on their reliability and safety. As such, the vehicles have not been on the road long enough to be considered ‘tested’ (BERR, 2008). Because of these issues, the public is unfamiliar with EVs which discourages consumer adoption (Sovacool and Hirsh, 2009). Therefore the reasons why some consumers have adopted EVs needs to be identified to better understand the demand side of the market.

One of the difficulties limiting the early adoption of a radical innovation such as electric vehicles (EVs) is the capture of a receptive consumer market (Christiansen, 1997). The literature has identified several reasons why fleet managers are good candidates to be EV early adopters such as their intense usage and high automobile purchase rates. This expectation is supported by a recent report from Frost and Sullivan (2013) which found that to 2013, governments and firms have been responsible for a majority of EV purchases. The research question of this sixth chapter is, *what were the important factors that influenced fleet managers’ initial adoption of EVs?*

1.7. Scope, data, and methods

This section identifies the research scope, data, and methods that were used for analysis. The complexity and breadth of the EV innovation process results in it being much too large to address in a single study. As such, the scope of this thesis was limited primarily to the role of auto manufacturers during EV market introduction with attention also devoted to consumer financial incentives and early adopters. While some chapters (3 and 4) deal with the broader timeframe of 1991-2011, a majority of the analyses focus on the recent buildup of EV expertise and the introduction of production models since approximately 2007. This approach allows the thesis to concentrate on recent actions and dynamics within the EV industry. Because innovation is not confined within a country’s borders and auto manufacturers are multi-national corporations, these studies generally take a global perspective, although Chapter 6 examines early adopters from the Netherlands and US.

Since a goal of this thesis is to study the emerging state of the EV industry, the constantly changing market environment creates data issues because information needs to be both current and reliable. Accordingly, analyses herein depend on up-to-date data e.g., vehicle prototypes, public charging station maps, and inter-firm alliances. In this regard, individual

studies make use of proven collection and analysis methods when dealing with publicly available information.

This thesis employed both inferential and descriptive analytical methods, including content analysis (both qualitative and quantitative), linear regression using ordinary least squares, t-tests, and frequency distributions. Individual chapters 2-6 provide more specific detail about the methods used for each analysis.

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2. Developing the knowledge for radical innovation

Sierzchula W., S. Bakker, K. Maat, B. van Wee (2014) Alliance formation in the automobile sector during an era of ferment, in: *Creativity and Innovation Management*, (in press)

Abstract

When developing radical innovations, firms often form collaborative relationships with external organizations to have access to additional resources. Therefore, alliance formation is influential in innovation and plays a key role in industrial change. However, most studies have not distinguished between individual alliances and instead aggregated collaborations when analyzing firm external R&D efforts. Our research sought to explore manufacturer use of alliances to acquire expertise in key knowledge areas as they developed and commercialized electric vehicles. Alliances from 24 manufacturers were analyzed according to type (explorative or exploitative), key knowledge area, and firm type (incumbent or startup). The results show distinct alliance formation patterns in different key knowledge areas. Heterogeneity of alliance formation in key knowledge areas indicates that developing a radical innovation is not as simple as acquiring new expertise. Rather it is a complex process where firms seek to develop their own knowledge base and use the expertise of other companies. This likely stems from a desire to develop technologies connected to core business models. Analyzing alliance formation according to key knowledge area provides a rich account of how firms approach knowledge acquisition as they develop radical innovations during a time of industrial uncertainty.

2.1. Introduction

During turbulent periods in an industry known as eras of ferment, existing and new firms develop radical innovations in response to emerging technological possibilities or changes in the market environment (Anderson and Tushman, 1990). Eras of ferment often mark the shift from one dominant technology to another e.g., cassette tapes to compact discs and represent crucial elements in industrial change (Dosi, 1982).

Dynamics in the automotive industry, such as increases in technological diversity and new firm entry, indicate that it may have entered the early stages of an era of ferment in the late 2000s (Sierzchula et al., 2012a). Virtually all car manufacturers are actively developing radical innovations in the form of electric vehicles (EVs), and forming alliances in order to gather the expertise necessary for those efforts.

Radical innovation requires a large amount of resources and a knowledge base different from that used in the dominant design (Teece, 1986; Tushman and Anderson, 1986; Powell et al., 2005). Firms can acquire new knowledge through in-house research and development (R&D) efforts and by partnering with external organizations that already possess this expertise (Koza and Lewin, 1998; Cassiman and Veugelers, 2006). However increasingly, firms have used an alliance approach in order to have access to the resources and knowledge necessary to develop radical innovations (Powell et al., 1996; Rothaermel and Deeds, 2004).

The combination of eras of ferment and calmer stretches of incremental innovation are referred to as the technology cycle with firms displaying different patterns of knowledge acquisition during these periods. During eras of ferment, firms created partnerships geared towards technical exploration (Van den Ven and Garud, 1994; Nesta and Mangematin, 2002). Once a dominant design emerged, businesses decreased their number of alliances and focused on internal methods of organizational learning (Rosenkopf and Tushman, 1998). From a practitioner's perspective, the literature shows how firms have used alliance formation to bridge gaps in expertise as they developed radical innovations.

A primary gap with the alliance literature is a lack of focus on the content of individual collaborations. Many studies do not distinguish between individual alliances, but instead aggregate them to analyze a firm's external R&D efforts (Rothaermel, 2001; Hagedoorn and Wang, 2012). Other empirical research has offered only limited analysis regarding the specific foci of alliances, largely whether collaborations were designed for knowledge exploration or exploitation (Beckman et al., 2004; Rothaermel and Deeds, 2004; Lavie and Rosenkopf, 2006; Rice and Galvin, 2006). These studies do not provide insight into how firms address alliance formation in the specific knowledge areas necessary for radical innovation.

A secondary gap involves the applicability of existing empirical evidence across sectors. As much of the alliance research has focused on biotech firms (Nesta and Mangematin, 2002; Rothaermel and Deeds, 2004; Hagedoorn, 1993; Powell et al., 1996; Ahuja, 2000), it is not known to what extent those results are applicable to other industries. Indeed, differences between the automobile and biotech sectors such as distinct industrial dynamics regarding firm size and knowledge generation could lead to separate approaches to alliance formation when developing a radical innovation. Furthermore, in the biotech sector, startup firms have been responsible for much of the new expertise (Rothaermel, 2001), while in the automotive industry, incumbents have largely driven radical innovation (Magnusson and Berggren, 2011).

The purpose of this paper is to reduce both gaps identified above through the following research questions. Firstly, how did individual automotive manufacturers use alliances to acquire expertise in knowledge areas that are important in the development and commercialization of electric vehicles? Secondly, to what extent are patterns of alliance formation relative to radical innovation similar across the biotech and automotive industries? Analyzing the foci of inter-firm collaborations according to knowledge domains should provide a better understanding of how firms approach external expertise accumulation as they develop a radical innovation.

2.2. Literature review and hypotheses formulation

Our research builds on two important threads of literature, the first being technology cycles and the second being the influence of alliance formation on innovation. These fields provide a theoretical foundation necessary for understanding EV developments as the auto industry finds itself in a period of high uncertainty with manufacturers forming alliances to acquire the expertise for creating an electric vehicle (a radical innovation) (Dyerson and Pilkington, 2005; Sierzchula et al., 2012a). Hypotheses are generated by combining those two threads of literature in the following areas: (1) the firm's approach to acquiring external expertise (explorative or exploitative alliances) (2) alliance formation in specific knowledge domains, and (3) relation of firm type (incumbent or startup) to alliance creation.

An important note about our research is that it is a case study of EV manufacturers and therefore, its results may have limited applicability to other industries. While the hypotheses below are derived based on general gaps within the literature, the results that emerge from our study are specific to the EV sector. However, because our article provides a basis for comparison with other industries, it may contribute to a more general understanding of how firms use alliances to acquire knowledge in the pursuit of developing a radical innovation.

2.2.1. Technology cycles

Technology cycles and their influence on industry are robust and well-defined in the literature with dominant designs and radical innovations demarcating eras of ferment and eras of incremental improvement (Utterback and Abernathy, 1975; Tushman and Anderson, 1986). The emergence of a radical innovation creates new market opportunities that require new areas of expertise (Anderson and Tushman, 1990). This situation, known as an era of ferment, disrupts incumbent control of the market and results in a flurry of activity as a host of new and existing firms seek to develop the innovation that will be most successful in the marketplace. As such, eras of ferment are characterized by increases in firm entry rate, industrial performance, technological variety, and high levels of uncertainty (Foster, 1986; Clark, 1985). These periods end when a dominant design emerges from the competing innovations to capture a majority of the market share (Abernathy, 1978). Eras of incremental change are characterized by low levels of uncertainty, a small number of principal incumbents, and competence enhancing improvements to the dominant design (Klepper, 1996; Tushman and Anderson, 1986).

It is important to note that although many technological changes have followed the general sequence of radical innovation → era of ferment → dominant design → era of incremental improvement → radical innovation (Tushman and Rosenkopf, 1992), this pattern is not applicable every time a radical innovation appears along with increases in firm entry and technological diversity. There are several instances where dynamics typifying an era of ferment have not led to the rise of a new dominant design. For example, in the 1990s, EVs were developed by automobile manufacturers and introduced to the market, but they

eventually faded away and the internal combustion engine (ICE) remained the dominant design. Additionally, industrial upheaval may lead to several technologies being successful in different market niches (Windrum and Birchenhall, 1998). This situation arises due to high levels of demand heterogeneity in different markets.

Eras of ferment always lead to the rise of a new dominant design, and thus can only be identified in retrospect (Tushman and Anderson, 1986). As such, it is impossible to say whether the current automobile industry, which has experienced increases in technological diversity, uncertainty, and firm entry, is actually in an era of ferment or not. The theory of technology cycles provides a useful perspective for understanding firm actions and the role of knowledge in innovation and thus is an important theoretical principle in our research. However, since we cannot knowingly identify the automobile sector as being in an era of ferment, we will instead refer the current situation as a period of uncertainty and industrial upheaval.

2.2.2. Alliance formation and innovation

The relationships of firms, alliances, knowledge, and innovation have evolved throughout the literature. The past fifty years has seen innovation move from large corporate laboratories to multi-firm networks. After World War II, large corporations such as DuPont, Xerox, AT&T, and GE developed innovations in company research centers (Schumpeter, 1942; Etzkowitz, 2003). Inventions to come out of such corporate research laboratories included cell phones, transistors, Kevlar, and the personal computer. There were examples of more progressive inter-firm relationships such as the Manhattan Project and the American Synthetic Research Program (Freeman, 1991), but businesses generally partnered with outside entities only for simple functions or to acquire news regarding external research and development (Nelson, 1990). However starting in the 1970s and 1980s, firms gradually increased collaboration efforts in order to reduce uncertainty and have access to each other's resources (Pfeffer and Salancik, 1978; Freeman, 1991). This was largely because radical innovation required a large amount of resources and a new base of knowledge. Few firms had the necessary expertise for radical innovation, leading to a rise in alliance formation between firms with complementary knowledge areas (Grant, 1996). Taking advantage of complementarities in key knowledge areas through collaboration has been specifically important for innovation in sectors with high levels of complexity e.g., biotechnology and new materials (Hagedoorn, 1993; Blomqvist and Levy, 2006). Indeed, Powell et al. (1996) and Nesta and Mangematin (2002) argue that in complex industries the locus of innovation now occurs not at the individual firm level but within networks of firms. Both Shan et al. (1994) and Ahuja (2000) support this notion by positively correlating the number of alliances with innovation output in the number of patents granted. In general, the literature has identified a positive relationship between a firm's tendency to form collaborative alliances and its ability to innovate. However it is worth noting that companies can suffer from a decline in long-term innovative performance through lowered internal R&D capabilities (Park and Kang, 2013)

Exploration and exploitation alliances

Alliances are used by firms in order to gain access to and make use of partners' resources and capabilities (Freeman, 1991). They can be categorized as *explorative* if they create new knowledge or *exploitative* if they build on and refine existing knowledge (March, 1991; Koza and Lewin, 1998). Explorative alliances are used in innovation and gaining new expertise e.g., R&D and joint ventures to develop new products (Cohen and Levinthal, 1990). Exploitative alliances are used for commercialization activities e.g., supplier and marketing

relationships. Explorative and exploitative alliances represent fundamentally different ways that firms interact with each other regarding knowledge.

The literature shows that the formation of explorative and exploitative alliances is associated with resource needs and availability. In mature industries i.e., those in which product innovation is predominantly incremental, firms are more likely to develop market access (exploitation) alliances (Hagedoorn, 1993). On the other hand, during periods of industrial instability, firms develop alliances geared toward technology and knowledge acquisition (Pyka, 2002; Rice and Galvin, 2006). During periods of industrial upheaval, firms often develop radical innovations, which require a large amount of resources and new expertise. Firms tend to form explorative alliances when they do not possess the knowledge or finances necessary to develop an innovation in-house (Carlsson and Stankiewicz, 1991; Tushman and Rosenkopf, 1992; Hagedoorn, 1993; Oliver, 2001; Nesta and Mangematin, 2002). When firms are developing radical innovations they tend to form explorative alliances regarding those technologies. This is done because explorative alliances are associated with the creation of an innovation instead of its commercialization. However it is also possible that companies may form exploitative alliances in those situations in order to bring their radical innovations to market.

Hypothesis 1: During a period of industrial upheaval, manufacturers seeking to develop electric vehicles (a radical innovation) will engage in a higher proportion of explorative as opposed to exploitative alliances.

Rothaermel and Deeds (2004) identified a correlation between product development and alliance formation as it relates to notions of uncertainty and firm expertise. They noted that in the product development stage (associated with high uncertainty and requiring new expertise), biotechnology firms were more likely to forge explorative alliances. As those products were commercialized (associated with less uncertainty and existing expertise) firms were more likely to forge exploitative alliances. Our study seeks to identify whether a similar alliance formation pattern exists during the product development stage for electric vehicles.

2.2.3. Key knowledge areas

As identified above, developing radical innovations involves expertise that is fundamentally different from that used in the conventional technology (Tushman and Anderson, 1986). Firms pursuing radical innovations must acquire the new expertise necessary for their development (Wuyts et al., 2004). Firms have been shown to form alliances in order to gain access to additional knowledge and experience (Hagedoorn, 1993; Koza and Lewin, 1998; Medina et al., 2005). In particular, firms have been shown to prefer explorative over exploitative alliances when developing radical innovations and gaining new expertise (Hagedoorn, 1993; Rothaermel and Deeds, 2004). Our research seeks to identify whether firms had specific alliance formation patterns in knowledge areas important in developing electric vehicles, namely: batteries, electric drivetrains, charging and infrastructure, and materials (IEA, 2011; Chan, 2007; Dyerson and Pilkington, 2005; German National Platform for Electro-mobility, 2012).

Hypothesis 2: During a period of industrial upheaval, EV manufacturers will forge a greater proportion of explorative (as opposed to exploitative) alliances in the key knowledge areas of batteries, electric drivetrains, charging and infrastructure, and materials.

2.2.4. Startup and incumbent firms

Startup and incumbent firms occupy prominent positions in both technology cycles and alliance formation literature. Some studies analyzing industrial change have noted that startups are more likely than incumbents to develop radical innovations (Foster, 1986; Christensen, 1997). Other research has shown the opposite to be true (Chandy and Tellis, 2000; Jiang et al. 2010). According to technology cycles, in an era of ferment there is a large influx of startup firms which consolidates down to a couple of large incumbents during an era of incremental improvements. However, it is the alliance literature which provides better guidance regarding how incumbents and startups will form alliances during periods of industrial upheaval. A resource-based explanation has been used to identify why startups are more likely than incumbents to form alliances (Colombo et al., 2006). Firms form alliances to have access to additional knowledge, resources, and experience (Freeman, 1991). Incumbents almost always have more resources than startup firms. This encourages startups (as opposed to incumbents) to form alliances in order to gain access to greater resources (Barabási and Albert, 1999). If firms have the resources necessary to develop and commercialize a product, then they will avoid forming alliances (Rothaermel, 2001). For this reason, as firms grow larger and accumulate a greater amount of resources, their tendency to form alliances decreases (Colombo et al., 2006). Incumbents (due to their abundance of resources) can be more selective in forging alliances while startups (driven to form alliance for legitimacy, resources, and experience) cannot be as discriminating in choosing their partners (Baum et al., 2000; Rothaermel, 2001).

One of the gaps in the literature is that it does not look at incumbent and startup alliance formation within the context of technological change. Characteristics of an era of ferment include a high level of uncertainty, firm entry rate, and technological diversity (Foster, 1986; Clark, 1985). During such periods of high uncertainty, both incumbents and startup firms are attempting to develop radical innovations (Rothaermel, 2001; Colombo et al., 2006). Since radical innovations require new expertise, firms are likely to seek out partners that can provide this new knowledge. The greater resources controlled by incumbent firms make them appealing as a partner and suggest that they will be able to successfully form alliances if that is their goal. The obvious counterexample is if a startup has expertise that other firms find desirable. Startups during periods of industrial upheaval usually possess the expertise necessary to develop radical innovations. In those situations startups will likely have partnership offers from firms seeking access to new expertise. Therefore the question becomes whether startups (likely with desirable expertise) will form more alliances than incumbents with a higher level of resources.

Hypothesis 3: During a period of industrial upheaval, incumbent electric vehicle firms will form a larger number of alliances than will startup electric vehicle firms.

2.3. Methods

We collected first level alliance data for electric vehicle manufacturers during the 2006 to 2011 timeframe. Figure 2-1 helps to visualize this data collection approach using a portion of the BMW alliance network. In Figure 2-1, BMW has alliances with Siemens, SB LiMotive (a joint venture between Bosch and Samsung), and AC Propulsion for a total of three alliances. Mitsubishi and Autoport are outside the immediate inter-firm network of BMW and thus would not be included among its alliances. Inter-firm networks were analyzed by looking at their development according explorative vs. exploitative alliances, key knowledge area, and

firm type. The remainder of this methods section identifies how the firms were selected, and how data was collected and analyzed.

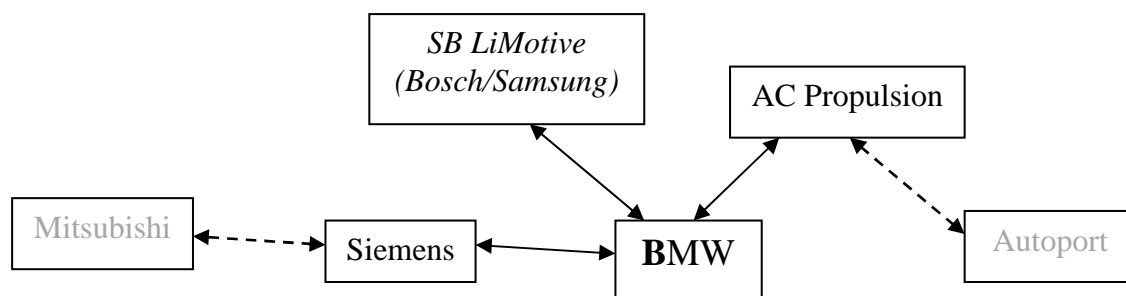


Figure 2-1: Sample of alliances for BMW

2.3.1. Firm selection

The study's purpose is to understand of how firms approached alliance formation in key knowledge areas as they developed EVs. In order to achieve that goal, the study sample was drawn from a population of EV manufacturers (to the authors' knowledge, the most exhaustive set available), and selected based on important factors which influence alliance formation. Sierchula et al. (2012a) identified more than 200 firms that developed an EV prototype or production model from 2000 to 2011. From that population, we selected a sample of 24 firms based on their size, geographic location, incumbent/startup status, and public availability of alliance data. Firm size and incumbent/startup status have been shown to be important factors in alliance formation (Colombo et al., 2006; Barabási and Albert, 1999). From a geographical perspective, we included firms from the three large production areas: North America, Europe, and Asia. Geographic location was used as a sample criterion because of differences in alliance formation patterns shown by companies from different countries (Hagedoorn, 2002). Finally, we did some preliminary data collection to identify whether firms had any alliance data that was publically available, excluding firms not having such data available.

The study sample included incumbent auto manufacturers that accounted for 75%¹⁴ of 2010 global vehicle production (OICA, 2011) and all startups that had publically available alliance information, coming to a total 24 firms. Incumbent firms were designated by having sold vehicles before 2000. The 17¹⁵ incumbent firms that we selected were: BMW, Chana, Daimler, FAW, Fiat, Ford, GM, Honda, Hyundai, Mahindra, Nissan, PSA, Renault, SAIC, Tata, Toyota, and Volkswagen. Early searches identified that although there were many startup firms that developed EVs during the 2000s, there were few with (publically) formalized alliances. The lack of startup EV manufacturers that had formed alliances limited the number of these types of firms that we included in our study to the following seven companies: Coda Automotive, Leo Motors, Mia Electric, Tesla Motors, E-Wolf, Venturi, and Zap. Based on this study sample, our conclusions should be generalizable for large auto manufacturers and well-financed startups. They are less likely to be relevant for smaller incumbents and startups without much financial backing.

¹⁴ This approach follows St Jean and Oltra (2009) in using large incumbent firms that make up a vast majority of vehicle production to analyze auto manufacturer R&D efforts.

¹⁵ All company subsidiaries were also included for each firm e.g., Audi, Skoda, Bentley, SEAT, and MAN are subsidiaries of Volkswagen.

We chose a time frame of 2006 to 2011 because it represents a transitional period when auto manufacturers brought electric vehicles to market and the industry began displaying many characteristics of an era of ferment including an increase in technological diversity as seen in battery chemistries, widespread exploration of niches, and lower barriers to firm entry (Magnusson and Berggren; 2011; Sierchula et al., 2012a; Sierchula et al., 2012b)

2.3.2. Data collection and analysis

Alliances were identified by analyzing company press releases and searching online automotive news resources.¹⁶ This approach to data collection has been used to populate several professional databases (Schilling, 2009) and has been the foundation for numerous academic articles (Hagedoorn, 1993; Powell et al., 1996; Rothaermel and Deeds, 2004; Rice and Galvin, 2006). In an analysis of alliance databases such as MERIT-CATI, SDC, and CORE, Schilling (2009) found them to yield reliable results and serve as an excellent source for inter-firm analysis. As we did not have access to those professional databases, we needed to create our own source of alliance data.

Our search queries included three elements (1) the name of the EV auto manufacturer, (2) "electric car OR vehicle OR drive OR automobile", and (3) one of the following terms: "venture", "supplier", "merger", "equity", and "partner". Using that approach, we explored the first 200 hits on news websites (per search query) and all hits on EV manufacturer websites. Based on this search, we populated our database with unique alliances related to EV development that involved one of the firms identified above in section 2.3.1. During preliminary research, alliances suitable for our database were identified in the first 125 hits on news websites. We chose to look at the first 200 hits to help ensure that we were able to capture all appropriate alliances. It is worth noting that all of the alliances in our database were found in the first 125 hits. Alliances were investigated to identify if and when they ended during the research time frame.

Each alliance was categorized as being either explorative or exploitative and its focus was identified relative to four key knowledge areas: batteries, electric drivetrains, charging and infrastructure, and new body materials. The explorative/exploitative designations were assigned by two investigators reading the specifics of each alliance and determining whether the collaboration sought to develop new knowledge (explorative) or build on and refine existing knowledge (exploitative). Textually, this distinction was made by the use of words such as 'supplier' or 'provider' for exploitative alliances and 'jointly develop' or 'cooperate' for explorative alliances. Similarly, determining which key knowledge area(s) were involved in each alliance was accomplished by reading the details of each collaboration. For example, Tesla and Daimler formed an explorative alliance geared toward jointly developing battery and electric drive components. A second example involved BMW establishing an exploitative alliance by using SB LiMotive as a battery supplier. In the first example, the alliance of Tesla and Daimler was established to create new expertise in the key knowledge areas of electric drivetrains and batteries; "*In order to benefit from each other's know-how, the investment enables the partners to collaborate even more closely on the development of battery systems, electric drive systems and in individual vehicle projects (Tesla, 2009)*" While in the second example, BMW used SB LiMotive's battery knowledge; "*BMW has selected SB LiMotive—the 50:50 joint venture between Bosch and Samsung SDI—as a supplier for Li-ion batteries for the upcoming Megacity vehicle*" (Greencarcongress, 2009). The difference in the two

¹⁶ These included www.greenautoblog.com, and www.greencarcongress.com

alliances is that BMW was not developing its own battery expertise, but was instead using that of SB LiMotive.

This study used inferential statistics to test the three hypotheses raised in section 2.2. To investigate Hypothesis 1, we divided alliances per firm into explorative and exploitative categories. A paired-sample t-test was used to determine whether there was a significant difference between the types of alliances formed by firms. Thereafter, a binomial analysis of variance identified whether firms were more likely to form a particular type of alliance. A similar statistical approach was used for Hypothesis 2, but t-tests and binomial analyses were applied to each key knowledge area instead of aggregated collaborations. For Hypothesis 3, we divided firms into incumbent and startup categories and summed the number of alliances they had formed. Then we employed an independent-sample t-test to identify whether there was a statistically significant difference in the number of collaborations created by the two types of firms. Descriptive graphs and tables were used to compliment the inferential analyses identified above, providing a visual representation of what was tested.

The study used investigator triangulation to validate the data and minimize biases (Denzin, 1970) with Krippendorff's alpha as a measure of intercoder reliability (Krippendorff, 2004). It is assessed on a 0 to 1 scale, with a value of 1 indicating perfect agreement and 0.9 being a commonly cited threshold for data reliability among social scientists (Neuendorf, 2002). Using a sample of the press releases¹⁷, two researchers identified the firms in the alliance, whether the collaboration was explorative or exploitative, and the key knowledge area resulting in a Krippendorff alpha of .925, attesting to the data's reliability.

2.4. Results

The results section uses alliance data from the EV industry and analyses identified in the methods section to address the hypotheses raised earlier in this article. Not all of the startup companies existed for each year of the study period. The analyses were corrected to reflect this.

2.4.1. EV network growth

Table 2-1 shows the yearly number of alliances, firms, and firms per alliance in the EV inter-firm network. During the study period, the number of alliances increased from 16 to 170, the total number of firms in the network increased from 24 to 154, and the average number of firms per alliance decreased from 1.50 to .91. There were also 16 alliances that ended during this period. Alliances that ended were not included in future year data.

Table 2-1: EV inter-firm network by number of firms and alliances

Year	Industry level network growth (cumulative)		
	Number of alliances	Number of firms	Firms per alliance
2006	16	24	1.50
2007	25	32	1.28
2008	48	66	1.38
2009	84	91	1.08
2010	125	124	0.99
2011	170	154	0.91

¹⁷ Following Lombard et al., 2004, the intercoder reliability check involved 10% of the data (20 press releases).

The general trend shown in Table 2-1 was an increase in the inter-firm network for the 24 EV manufacturers in our study. The decrease in the average number of firms per alliance indicates that firms became part of more than one alliance and that the network became 'denser' over the study period. Dense networks are characterized by increased connectivity and innovation among actors (Powell et al., 1996).

2.4.2. Exploration vs. exploitation alliances

We categorized alliances as being either explorative (creating new knowledge) or exploitative (building on and refining existing knowledge). The literature has found that firms generally forged explorative alliances during periods of uncertainty or as they move into new technological areas (Hagedoorn, 1993; Rothaermel and Deeds, 2004). Our research sought to determine whether firms forged a larger percentage of explorative as opposed to exploitative alliances during the recent period of industrial upheaval for the EV industry.

To do this, we used a paired-sample t-test on the two types of collaborations formed by firms to determine if there was a statistically significant difference in those two groups. This test resulted in a p-value of 0.042 allowing us to conclude that EV manufacturers displayed different formation patterns for those two alliance categories. Then, a binomial analysis of positive/negative variance allowed us to identify whether firms were more likely to create explorative as opposed to exploitative alliances. This test took for each firm the expected number of explorative and exploitative alliances (half of the firm's total alliances) and compared it to what was actually observed. If the number of observed explorative alliances was greater than the number of expected, then this variance was positive. For example, if firm X had 10 alliances, and six of them were explorative, that would result in a positive variance. This binomial test (success = 17, N = 24, P=0.5) produced a p-value of 0.021 establishing that firms did form more explorative as opposed to exploitative alliances resulting in support for hypothesis 1.

Supplementing that statistical analysis, Figure 2-2 provides a descriptive examination of the number of explorative and exploitative alliances for each year of the study from an industry-level perspective.

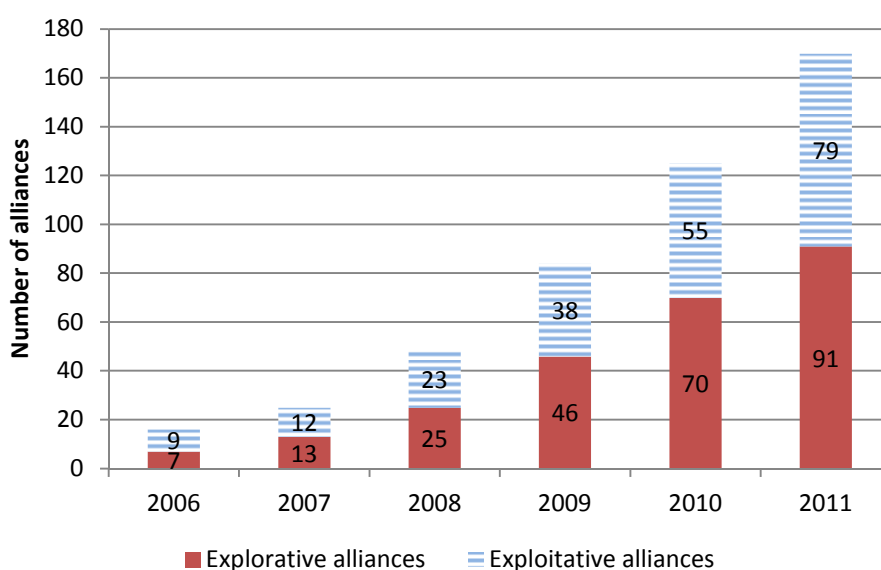


Figure 2-2: Distribution of explorative and exploitative alliances by year

Figure 2-2 shows that there were more explorative alliances in every year but 2006. Additionally, the number of explorative alliances grew at a faster annual rate than did the number of exploitative alliances (240% vs. 155%). However, the proportion of explorative and exploitative alliances moved within a tight range throughout the study period. Neither alliance type represented less than 44% or more than 56% of all alliances in a given year. Some of the exploitative alliances at the beginning of the study period can be explained by the level of EV commercialization at the time. In 2006, alliances from Mahindra (Reva) and Zap represented almost half of the alliances in our database. Mahindra and Zap were selling electric vehicles at the time and their alliances were primarily geared toward exploitative relationships. However as the EV inter-firm network expanded, the Mahindra and Zap exploitation alliances represented an increasingly smaller proportion of all alliances in the study. Over the study period there were very few other electric vehicles brought to the market, so the notion that a large number of exploitative alliances in Figure 2-2 were related to commercialized EVs does not hold.

2.4.3. Alliance formation patterns in key knowledge areas

The literature identified the following four knowledge areas as being important to the development of electric vehicles: batteries, electric drivetrains, charging and infrastructure, and materials (IEA, 2011; Chan, 2007; Dyerson and Pilkington, 2005; German National Platform for Electro-mobility, 2012). We used alliance formation patterns to explore how firms approached those domains of expertise. Hypothesis 2 asserted that firms would form more explorative as opposed to exploitative alliances in important knowledge areas.

To test that hypothesis, we divided all of the alliances for each key knowledge area into categories of explorative and exploitative. Then we ran a paired-sample t-test to determine whether there was a statistical difference in those groups. The p-values for each of the key knowledge areas are provided below in Table 2-2.

Table 2-2: P-value from paired-sample t-tests in key knowledge areas

	Batteries	Electric Drivetrain	Charging & Infrastructure	Materials
Paired-sample t-test (p-value)	0.038	0.001	0.096	0.034

Those results indicate that there was a statistical difference in the number of explorative and exploitative alliances that auto manufacturers formed in the key knowledge areas of batteries, electric drivetrains, and materials (not charging & infrastructure). To further determine whether this difference indicated a tendency to form more explorative alliances in a particular knowledge area, we used a binomial analysis of variance looking at expected vs. observed values. The p-values from this test are displayed below in Table 2-3:

Table 2-3: P-value from binomial analysis of variance in key knowledge areas

	Batteries	Electric Drivetrain	Charging & Infrastructure	Materials
Binomial analysis (p-value)	0.094	0.007	0.148	0.07

The binomial analysis shows that only in the category of electric drivetrains was there a statistically significant result showing that auto manufacturers formed more explorative as opposed to exploitative alliances. The results shown in Tables 2-2 and 2-3 indicate mixed support for Hypothesis 2.

For a graphical representation of the analysis above, Figure 2-3 shows an industry-wide overview identifying the total number of exploration and exploitation alliances formed in each of the four key knowledge areas.

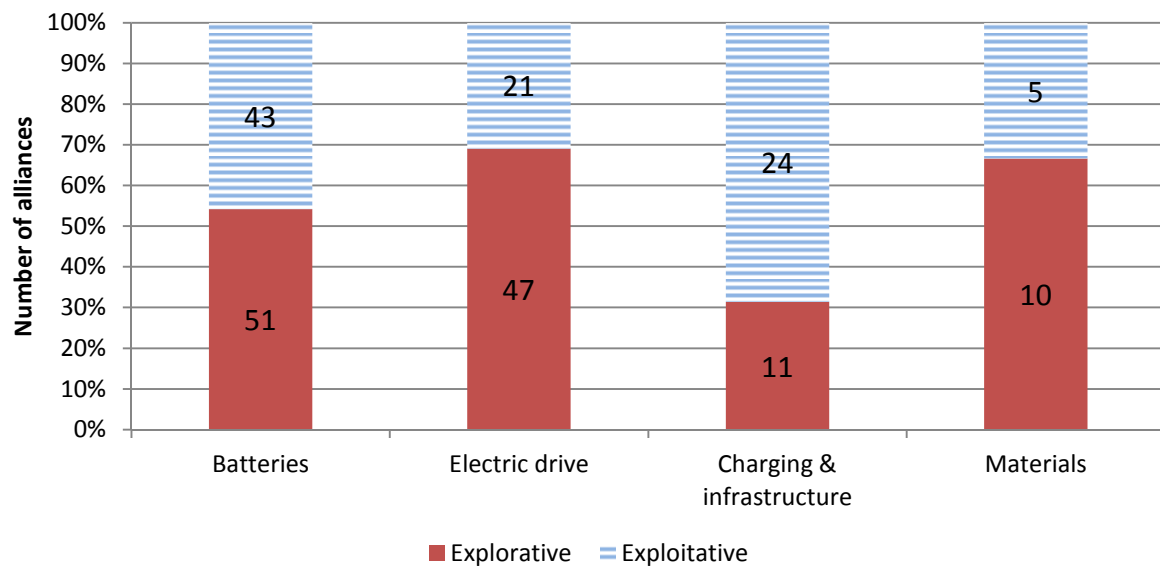


Figure 2-3: Explorative and exploitative alliances in key knowledge areas

Over the study period, firms developed almost an even number of explorative and exploitative alliances regarding batteries. They developed more explorative alliances in electric drive and materials, suggesting a desire to eventually bring that knowledge in-house. Charging and infrastructure was the only knowledge area with a larger proportion of exploitative alliances. This is likely because charging and EV infrastructure are issues being addressed by other types of organizations e.g., government bodies and utilities.

The overview in Figure 2-3 does not identify how individual firms approached alliance formation in key knowledge areas. Thus we do not know whether a couple of firms made many explorative alliances in electric drive while other firms did not have any alliances in that knowledge area.

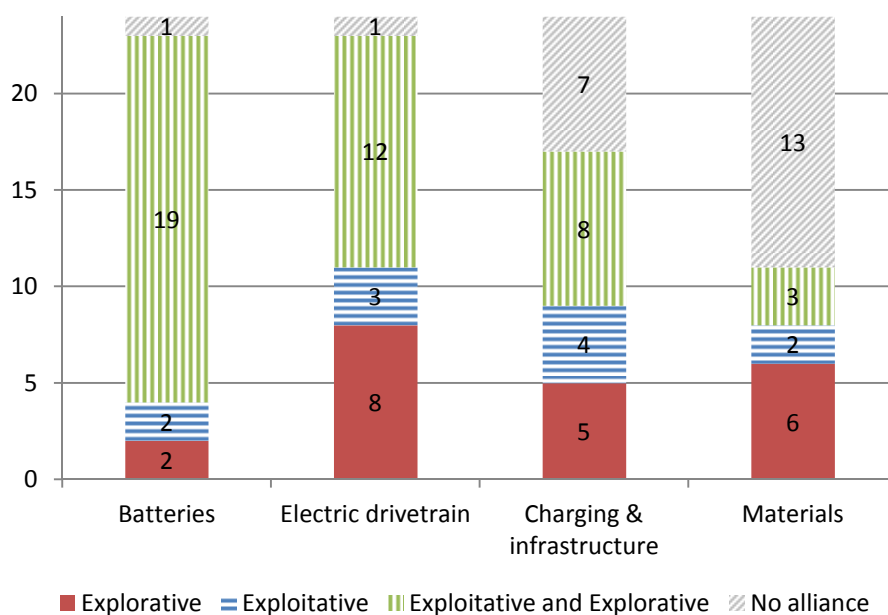


Figure 2-4: Explorative and exploitative alliances in key knowledge areas by firm

Figure 2-4 attempts to address this shortcoming by showing whether individual firms formed explorative alliances, exploitative alliances, or both in key knowledge areas. For example, Coda Automotive had a battery supplier alliance with Yardney Technical Products and a battery joint venture with Lishen Energy Systems. In that example, Coda Automotive pursued both exploitative and explorative alliances in the batteries domain of expertise.

Similar to Figure 2-3, Figure 2-4 shows that firm approach toward developing explorative and exploitative alliances varied by knowledge area. Most firms (19 out of 24) developed both explorative and exploitative alliances in batteries. After batteries, the number of firms that developed both types of alliances steadily decreased across electric drivetrain, charging and infrastructure, and materials. Figure 2-4 largely reinforces Figure 2-3 except in charging and infrastructure. Figure 2-3 shows more than twice as many exploitative alliances in charging and infrastructure while Figure 2-4 shows a more even distribution of alliance type. This difference is due to the large amount of exploitative alliances made by Nissan and Renault in charging and infrastructure.

2.4.4. Incumbent and startup alliance formation

The literature has shown that startup firms are more likely to form alliances than larger incumbents. Our review of the technology cycle and alliance literature revealed that both startups and incumbents develop radical innovations. While startup firms are more likely to form alliances, both firm types seek to form explorative alliances during periods of high uncertainty or when moving to a new technological field. Hypothesis 3 stated that incumbents would form a larger number of alliances than would startup firms.

To test that hypothesis, we divided firms into incumbents and startups and then used an independent-sample t-test to analyze the difference in the number of alliances they formed. The p-value of that test was 0.027 indicating statistical significance. Since incumbents formed an average of 20 alliances vs. 10 for startups, we can further conclude that the larger

firms were more likely to form a greater number of collaborative relationships than their smaller competitors. Thus, our analysis provides support for Hypothesis 3.

To show how this data changed by year, Table 2-4 displays the average number of explorative and exploitative alliances formed by startup and incumbent firms throughout the study period. It is important to note that in Table 2-4, alliance averages were only calculated among firms that participated in the EV network (that had at least one alliance). Also, some alliances included more than one of the EV manufacturers in our study.

Table 2-4: Average number of explorative and exploitative alliances per firm type by year

	2006	2007	2008	2009	2010	2011
Incumbent explorative	1.2	1.6	1.4	2.8	4.4	5.8
Startup explorative	0.5	1.2	1.5	2.1	3.4	4.0
Incumbent exploitative	0.7	1.0	1.2	1.9	3.0	4.7
Startup exploitative	1.5	1.2	1.7	2.0	2.7	3.0

Table 2-4 shows that the average number of explorative and exploitative alliances for startup and incumbent firms increased throughout the study period. Incumbents in general ended up with a higher average number of both explorative and exploitative alliances than did startups.

2.5. Discussion

We tested hypotheses derived from the literature regarding alliance formation in key knowledge areas during periods of industrial upheaval. This section provides discussion based on the results of those hypotheses as well as the theoretical and practical implications from our findings.

Hypothesis 1 stated that during periods of industrial upheaval, EV firms would forge a higher proportion of explorative as opposed to exploitative alliances. This hypothesis was statistically supported by the results. However in addition to explorative collaborations, firms also formed a large number of exploitative relationships. This differed from the results of previous studies that found that biotech firms primarily formed explorative alliances as they were developing radical innovations (Hagedoorn, 1993; Rothaermel and Deeds, 2004). Therefore, our research calls into question the nature of the relationship between alliance type and radical innovation, specifically across industrial sectors. An interesting follow-up to this research would be to analyze the reason for the difference in alliance formation pattern between EV and biotech industries.

Hypothesis 2 asserted that EV firms would be more likely to form explorative as opposed to exploitative alliances in important expertise domains. Statistical tests showed that firms displayed significant differences in their alliance formation patterns within key knowledge areas. Although manufacturers formed more explorative alliances in three of the key knowledge areas (not including charging and infrastructure), the results were only statistically significant for electric drivetrains.

This distinction in alliance formation regarding different domains of expertise provides an important contribution to innovation theory. Developing radical innovations involves incorporating a new knowledge base into an existing platform (Tushman and Anderson, 1986). Therefore, treating all alliances the same can overlook variation in how firms attempt to acquire expertise in different domains. Analyzing alliance formation by knowledge area

can provide a better idea of how firms have approached the development of radical innovations.

From a practical standpoint, distinct alliance formation patterns relative to specific knowledge areas point to different strategic approaches by EV manufacturers. Based on our paper, it is possible to conclude that the number of alliances that manufacturers formed in knowledge areas was relative to distance from existing core competencies or where the firms would like their core competencies to be in the developing technology. For instance, EV manufacturers would rather have a core competency in batteries than in charging infrastructure. Thus, studying alliance formation in key knowledge areas could identify corporate strategies regarding how firms want to position themselves in the development of a radical innovation and its future value chain.

Hypothesis 3 stated that during periods of industrial upheaval, incumbent EV firms would form a larger number of alliances than would startup firms, which was statistically supported by our results. As both firm types were expected to seek alliances to provide expertise necessary to develop electric vehicles, our results indicate that during a time of industrial uncertainty, incumbents were able to use their greater level of resources to successfully form alliances. This likely provided incumbents with a competitive advantage over startups in the EV industry and supports the existing literature regarding alliance formation by the two types of firms (Baum et al., 2000; Rothaermel, 2001). A practical implication is that EV startups will need to seek avenues other than alliances in order to develop a competitive advantage over incumbents, for example by developing expertise in specific knowledge areas in-house. These results also could help explain why there have been so few startup firms that have actually commercialized an electric vehicle.

2.6. Conclusions

This article used alliance formation patterns by EV manufacturers to provide insight into inter-firm collaboration during the development of a radical innovation. In answering the first research question, our study found that firms displayed distinct alliance formation patterns within key knowledge domains, preferring explorative collaborations in areas of expertise where they would like to have core competencies e.g., batteries and electric motors. Regarding the second research question, we found that firms formed more exploitative alliances than would be expected at such an early stage of innovation development (based on earlier research of biotech firms). However, the large number of exploitative alliances that manufacturers formed indicates that they developed collaborations to simultaneously pursue both commercialization and knowledge acquisition. This approach would allow manufacturers to use exploitative alliances to bring EVs to market quickly while at the same time investing in explorative alliances to establish the necessary expertise in-house so that they could develop the next generation of automobiles on their own. Lastly, large incumbents formed a greater number of alliances than did startups, providing them with a competitive advantage and indicating the value of their greater level of resources.

2.6.1. Study limitations

Several limitations arise from our research, specifically because of its use of alliances and as it only analyzed one industry. The data collection method in general may have suffered due to lack of the public availability of certain collaborations, biases for Anglo-Saxon sources, and underestimation of specific types of alliances such as licensing. In addition, because not all alliances are of equal value, they likely provided only a rough approximation of a firm's innovative efforts. This shortcoming could be addressed by interviewing managers directly

involved in research to identify the value of individual alliances. Finally, by only analyzing EV manufacturers, our research has limited generalizability to other industries. However, this approach does have the benefit of enhancing internal validity by controlling for exogenous factors.

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3. Commercializing alternative fuel vehicles

Sierzchula, W., S. Bakker, K. Maat, and B. van Wee (2012) Technological diversity of emerging eco-innovations: a case study of the automobile industry, in: *Journal of Cleaner Production*, 37, 211-220.¹⁸

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 a 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.

¹⁸ Relative to the journal article version, minor changes were made to Figures 3-5 through 3-13 to better explain the figure's contents.

3.1. 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)¹⁹. 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)²⁰ 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 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,

¹⁹ 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.

²⁰ 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.

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 3.2) that reviews foundational theoretical elements used in our article (technological transitions, incumbents, and eco-innovations). Section 3.3 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 3.4. Section 3.5 presents and discusses the results of this analysis from an industry, technology, and firm level. Lastly, Section 3.6 provides concluding statements that highlight the main points of this research along with policy recommendations.

3.2. Theory

3.2.1. 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).

3.2.2. 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).

3.2.3. 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).

3.3. 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.

3.3.1. 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 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’. Figure 3-1 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 Figure 3-1, 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 socioeconomic 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 (H₂ 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.

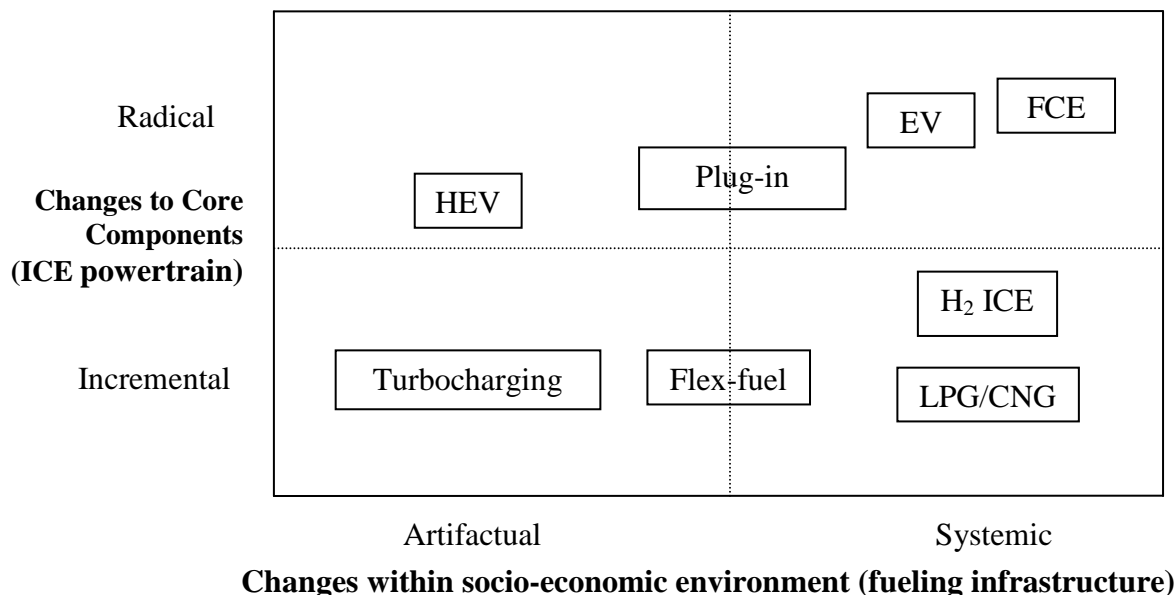


Figure 3-1: Powertrain innovations relative to the ICE powertrain and fueling infrastructure
(based on figures from Henderson and Clark, 1990 and Hekkert et. al, 2005)

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).

3.3.2. 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 powertrain architecture or the fuel that they use. Table 3-1 shows the AFVs included in our study: flex-fuel, LPG, CNG, H₂ ICE, HEV, EV, and FCEV. Table 3-1 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 3-1 shows that the alternative fuel powertrains in our study offer lower vehicle emissions (CO₂ and toxic substances)²¹ and fuel costs, but face barriers of high purchase costs

²¹ 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, CO₂ 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.

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.

Table 3-1: 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

3.3.3. 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 3-2²² 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

²² 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.

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 3-2, 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 (w7.7% of US vehicle sales since 2005) and HEVs (w2.5% 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).

Table 3-2: 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 Elektrisch Vervoer	Subsidy/tax on vehicle efficiency
Supply-side	Marketing	Centrum	Informs potential EV customers
	Regulation	ZEV mandate	Number of zero-emissions vehicles
		EU emissions	Vehicle emissions
	Financial	CAFE	Fuel efficiency
Infrastructure	Financial	2005 US Energy Policy Act	Tax credits to ethanol producers
		ARPA-E	Low-interest loans to AFV companies
Land use		Amsterdam Elektrisch	Refueling stations
Pilot projects		Amsterdam Elektrisch	Free parking in Amsterdam for EVs
		HyFleet	FCEV demonstration project
Public transport		NY fleet	HEV buses in municipal fleet

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).

3.3.4. Alternative fuel vehicle sales

As identified in Figure 3-1, 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 3-3²³ supplies the number of AFVs that were sold, leased, or converted in the US from 2000 to 2009. Table 3-4 gives AFV production statistics for Japan from 2000 to 2009. Trends in Table 3-3 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 3-4 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 3-3 and 3-4 include more firms than our own analysis and may include niche market vehicles that incumbents typically do not produce. Therefore the statistics in Tables 3-3 and 3-4 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.

²³ Tables 4-3 and 4-4 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.

Table 3-3: Vehicles sold, leased, or converted in the US from 2000-2009 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	9,501	11,121	8,988	6,122	7,752	3,304	3,128	2,487	4,440	3,770
EV	6,215	6,682	15,484	12,395	2,200	2,281	2,715	3,152	2,802	2,255
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	9,350	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	4,435	3,201	1,667	2,111	2,150	700	473	356	695	126

Table 3-4: Vehicles produced in Japan from 2000-2009 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	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

3.4. 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 powertrains. Specifically, we looked at how AFV powertrains have been developed from an industry, technology, and firm level. As Tables 3-3 and 3-4 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 HEV²⁴ 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

²⁴ 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.

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.

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.

3.5. Results

3.5.1. Industry level

Figures 3-2 through 3-4 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. Figure 3-2 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. Figure 3-3 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 3-4 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 3-2 through 3-4 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.

Table 3-5 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.

3.5.2. Technology level

Figures 3-5 and 3-6 present the three year average of the number of prototype and production models that were presented for each AFV technology. Those figures complement Table 3-5 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 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.

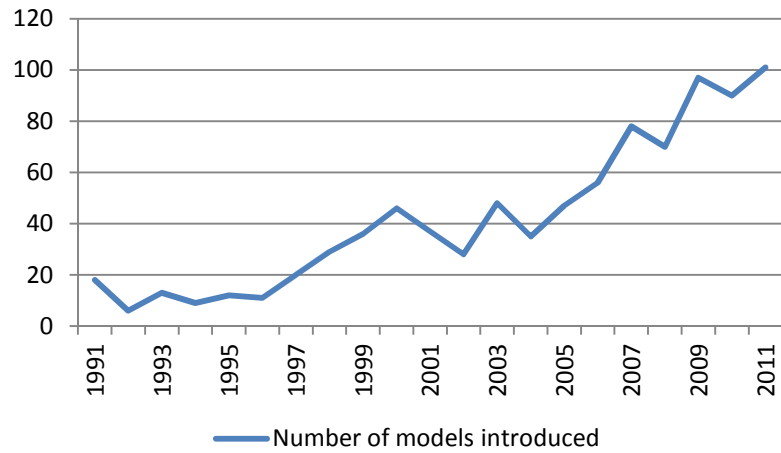


Figure 3-2: Number of AFV models introduced

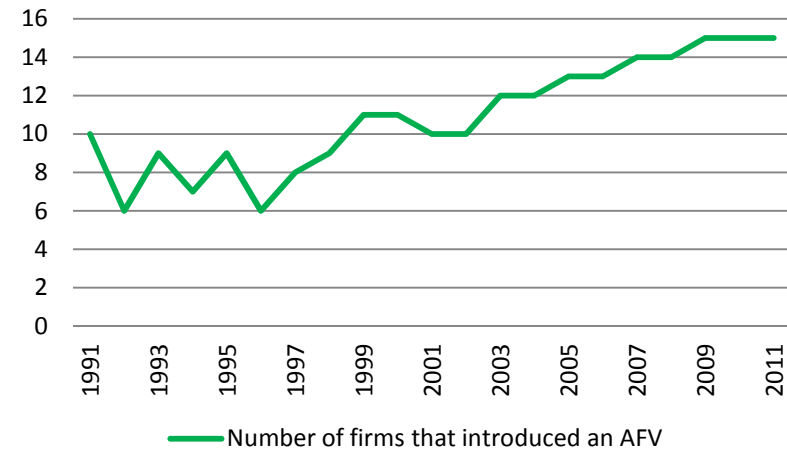


Figure 3-4: Number of firms that introduced an AFV model

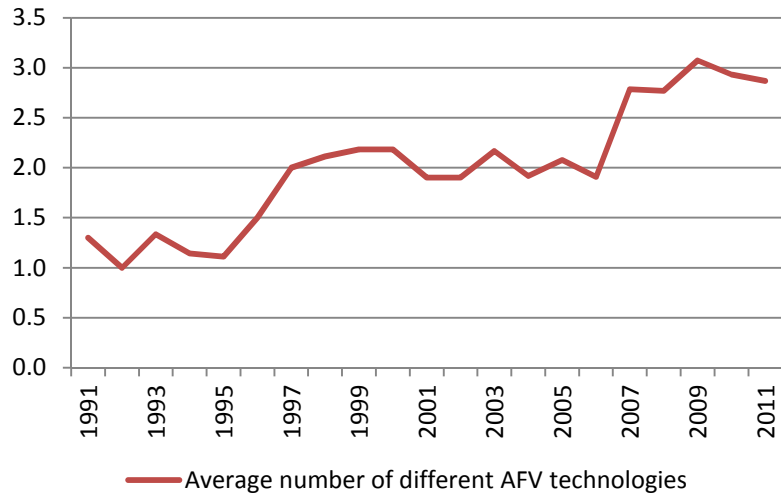


Figure 3-3: Average number of different AFV technologies presented by manufacturers

Table 3-5: 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	377	884
	(100%)	(100%)	(100%)

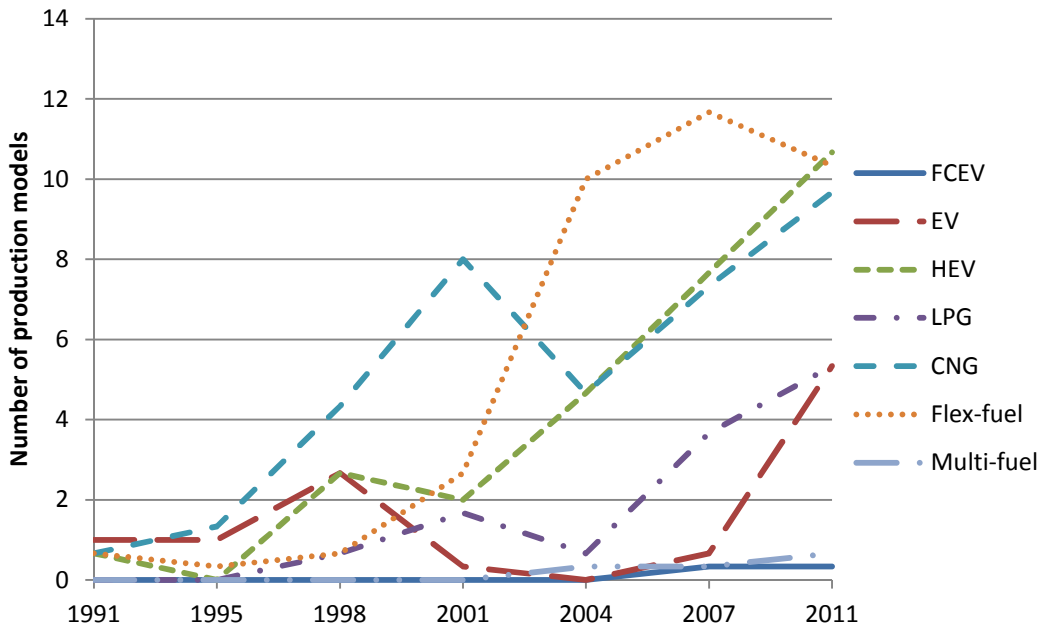


Figure 3-5: Moving 3 year average of AFV production model introductions from 1991 to 2011

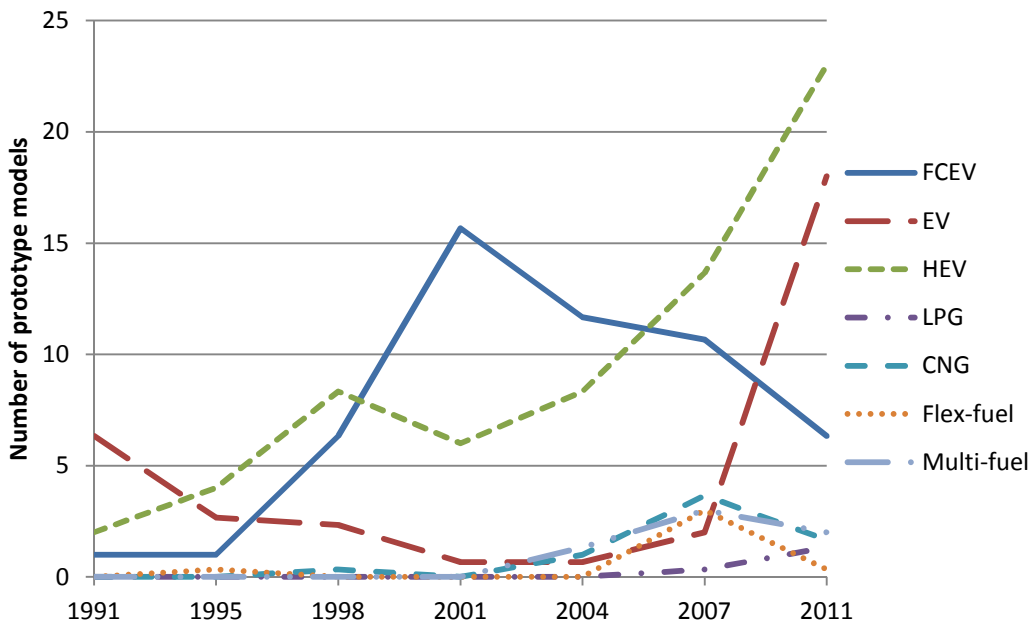


Figure 3-6: Moving 3 year average of AFV prototype model introductions from 1991 to 2011

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 3-3 showed that flex-fuel vehicles have an established market as opposed to hydrogen vehicles which are still in the pre-adoption phase of commercialization. Figures 3-5 and 3-6 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 Figures 3-5 and 3-6 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 Figures 3-7 through 3-12.

Figures 3-7 through 3-12 show the number of manufacturers and models with AFV technologies that were introduced from 1991 to 2011. Even though Figure 3-2 shows that the annual number of AFV models introduced has increased, Figures 3-7 through 3-12 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 its vehicle lineup. However as a whole, the number of models using those technologies displayed a general increase during the 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, Figures 3-7 through 3-12 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 Figure 3-12 (flex-fuel vehicles) from 1991 to 2011, Figure 3-7 (EVs) from 1999 to 2007, and Figure 3-8 (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.

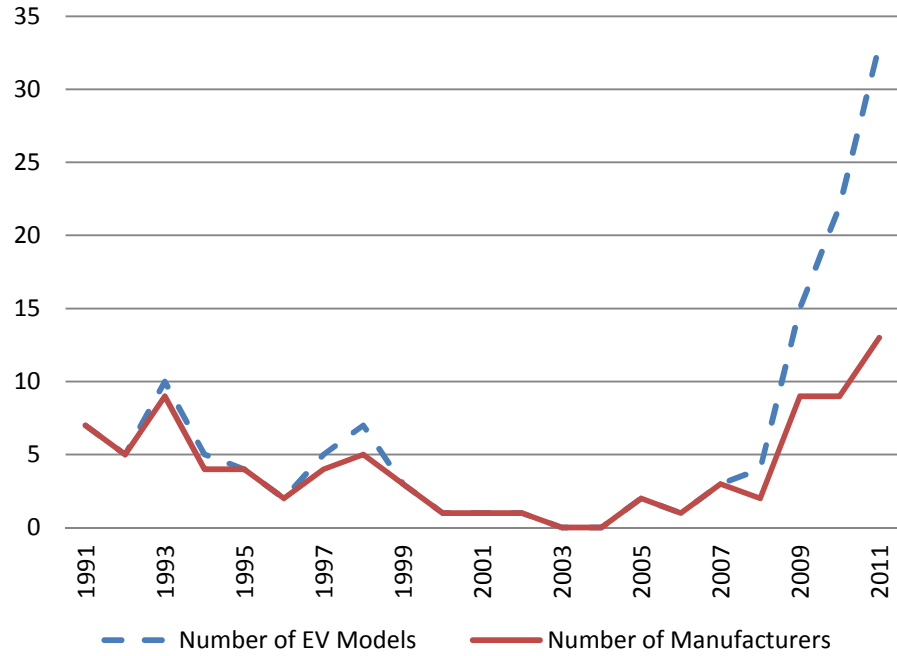


Figure 3-7: Electric vehicle model introductions

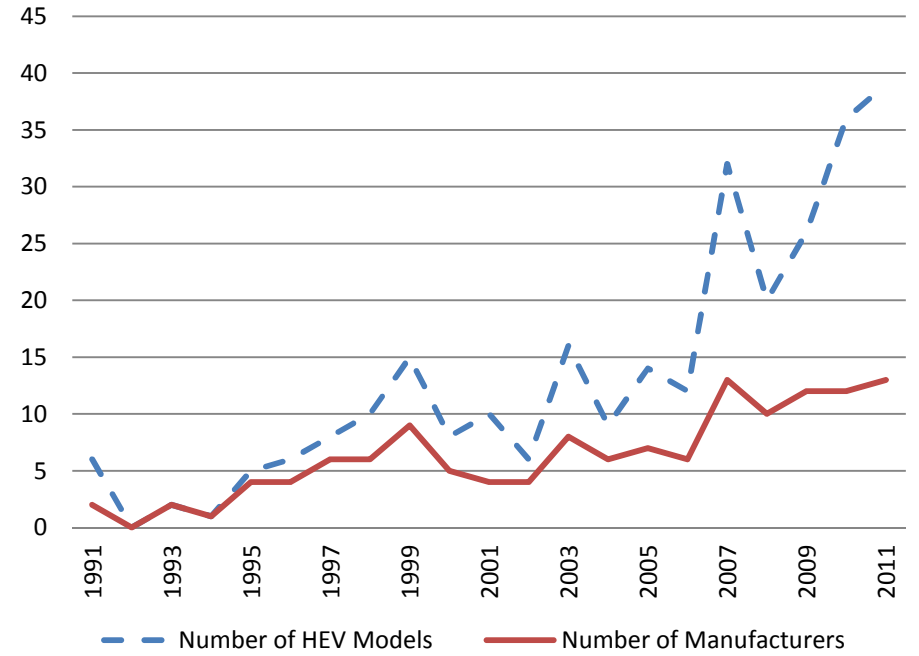


Figure 3-8: Hybrid-electric vehicle model introductions

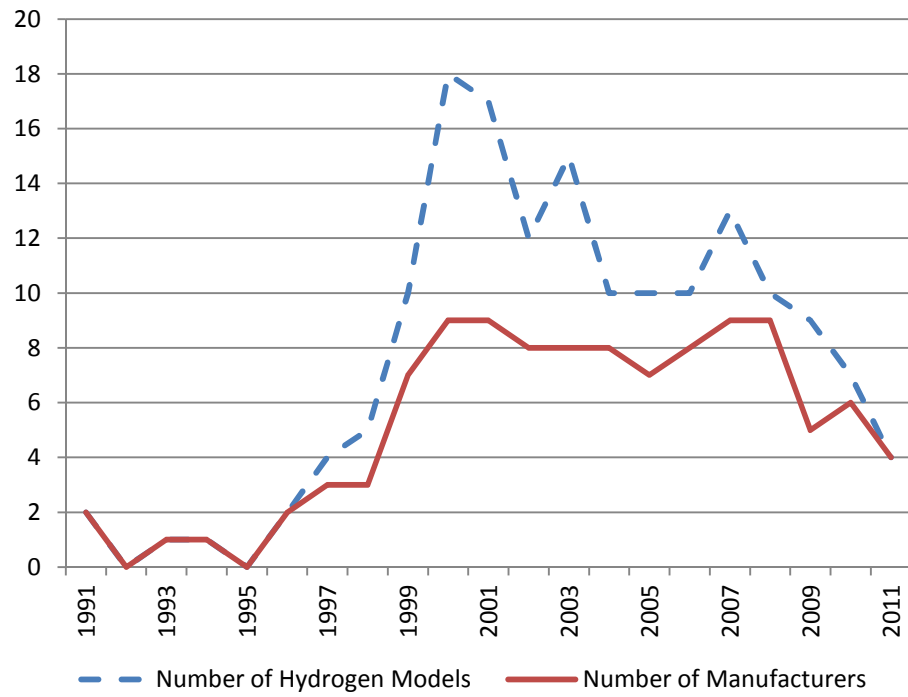


Figure 3-9: Hydrogen vehicle model introductions

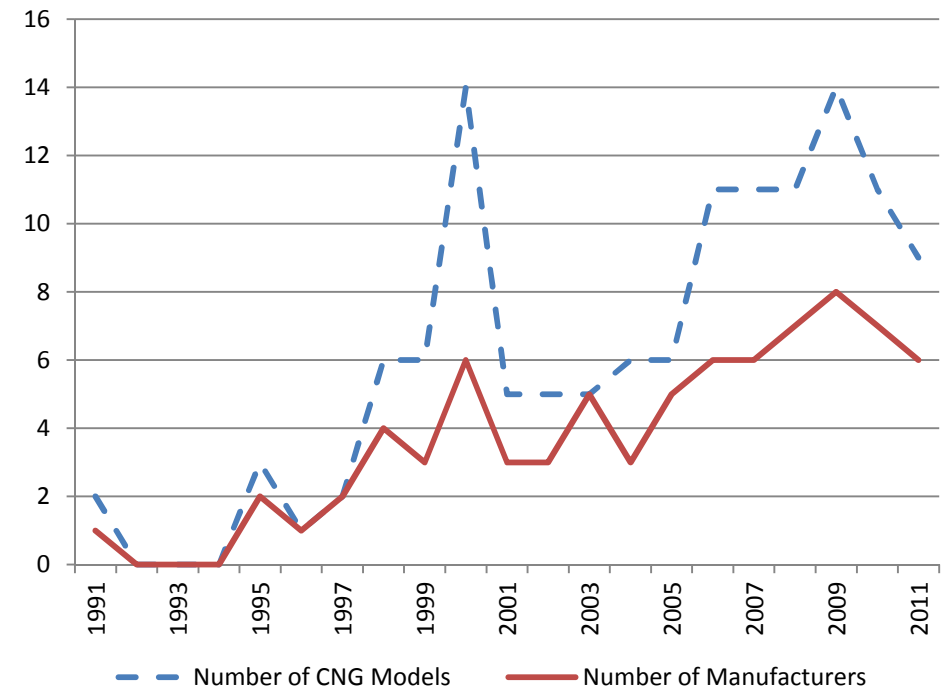


Figure 3-10: CNG vehicle model introductions

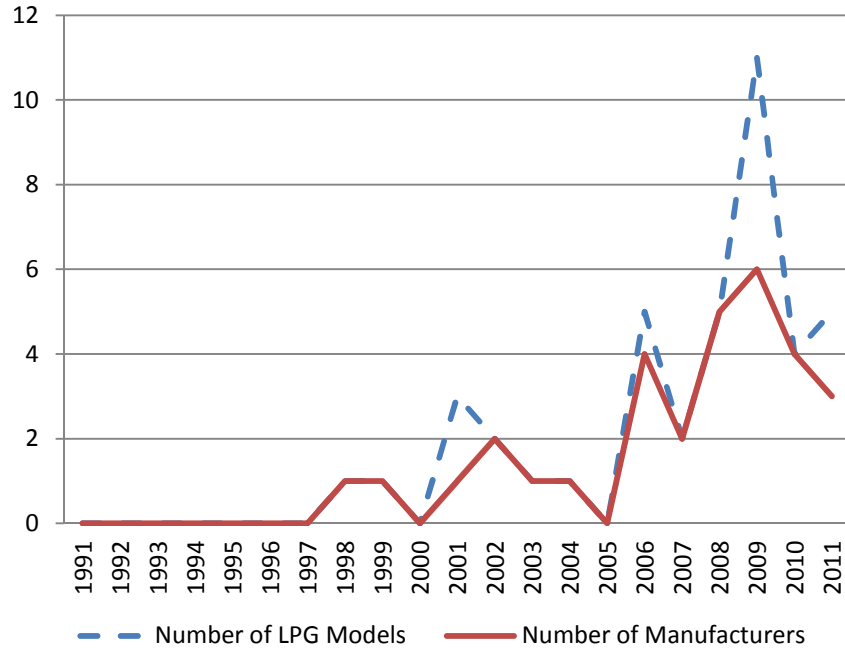


Figure 3-11: LPG vehicle model introductions

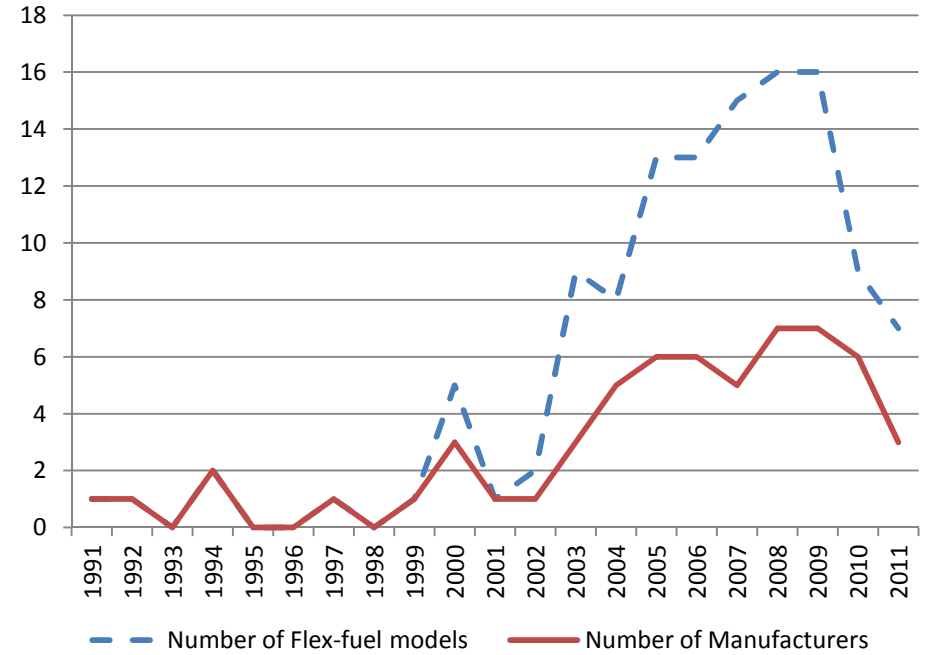


Figure 3-12: Flex-fuel vehicle model introductions

3.5.3. Firm level

Figure 3-13 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).

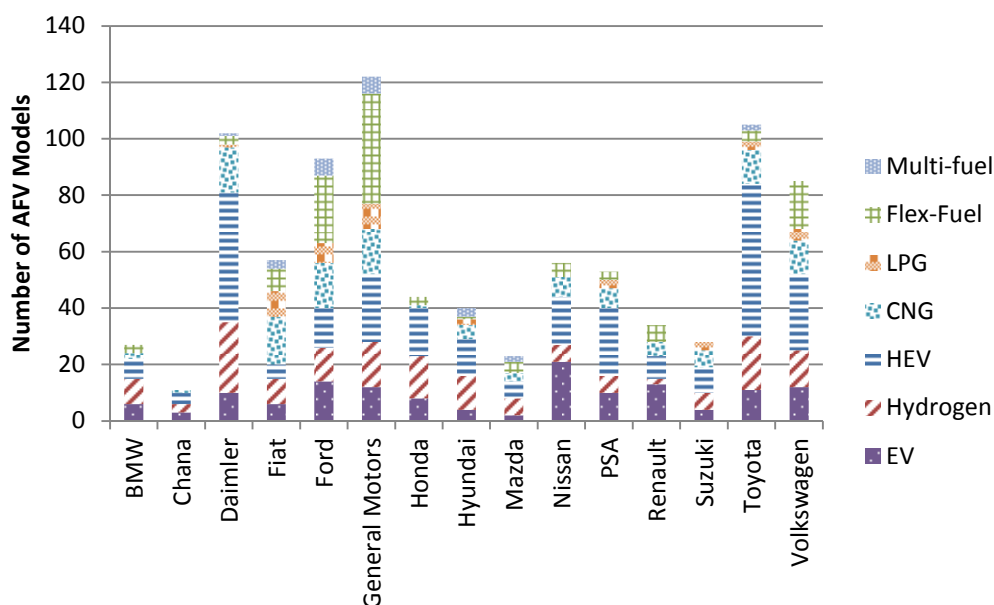


Figure 3-13: Number and type of AFV models introduced by individual incumbent auto makers

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 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.

3.6. Conclusions and policy recommendations

3.6.1. 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 3-3 and 3-4 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).

3.6.2. 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 adoption 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 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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4. The emerging electric vehicle market

Sierzchula, W., S. Bakker, K. Maat, and B. van Wee (2012) The competitive environment of electric vehicles: An analysis of prototype and production models, in: *Environmental Innovation and Societal Transitions*, 2, 49-65.²⁵

Abstract

This study analyzes the industrial dynamics of electric vehicles using product life cycle and eco-innovation concepts. A unique database of approximately 450 electric vehicle prototype and production models from 1991 to 2011 was collected and analyzed. This research largely focused on three factors that become fluid during a transitional era of ferment (the technology, the set of firms and the target market). Results show that since 2004, the number of companies producing electric vehicle (EV) models has substantially increased with startup firms comprising a majority of that growth. The variety of battery types used in EV models has expanded, largely through lithium-ion chemistries. Large incumbents and startup firms have targeted different consumer markets with their EV models. Startup firms developed EV models for niche markets (sports cars and low speed vehicles) while large incumbents generally developed EV models that are more in line with current customer demands.

²⁵ Relative to the journal article version, a minor change was made to Figure 4-2. The Figure now indicates fuel displacement in terms of liters instead of cubic centimeters.

4.1. Introduction

The automotive industry has been dominated by the internal combustion engine for more than a century. This dominance is being challenged by a number of radically innovative powertrains of which the pure battery electric vehicle (EV)²⁶ is a prominent contender. EVs are not a new innovation, and have experienced a turbulent history over the past 100 years from their rise and fall during the introduction of motorized vehicles in the early 1900s (Mom, 1997) to a recent resurgence in attention from firms and governments (IEA, 2011). The 1990s saw a renewal of interest in EVs primarily due to the California Zero Emissions Vehicle (ZEV) mandate, which enforced the production of non- CO₂ emitting vehicles (e.g. electric vehicles) by manufacturers. The ZEV mandate prompted the development of several EV production vehicles from large auto manufacturers (Dijk and Yarime, 2010). Large auto makers viewed ZEV as being unduly burdensome and challenged it in court in 2001. This challenge resulted in an amendment in 2003 to require fewer emissions-free vehicles, and EVs largely receded from media's attention and auto makers' R&D plans (Bedsworth and Taylor, 2007). Even though the ZEV mandate did not succeed in forcing the introduction of zero emissions vehicles, it did lead to the development of hybrid-electric vehicles (HEVs) and low-emission vehicle technology (Pilkington and Dyerson, 2006). The primary issue that has challenged the adoption of EVs in the 1990s, and that continues to be the greatest barrier, is the trade-off between battery performance (top speed and driving range) and vehicle cost (IEA, 2011). To this point, EVs have not been able to offer a reasonably priced alternative to an internal combustion engine (ICE) automobile with a comparable driving range. This has led to EVs largely appearing in niche markets such as low speed vehicles (LSVs) or as prototypes exhibiting technological advances (Van Bree et al., 2010). They have not been able to compete in the mainstream markets where the majority of automobiles are sold. However, it seems that the automobile industry currently finds itself in the early stages of a so-called era of ferment in which the stable regime of the ICE and a more or less fixed set of firms is threatened by new technologies and new manufacturers (Magnusson and Berggren, 2011). Our paper represents an effort to help explain the industrial dynamics that are both cause and effect of the recent resurgence of the electric vehicle.

There have been various studies which examined the automotive industry with respect to electric vehicles. A growing body of literature deals with the questions of whether EVs will be successful and the conditions under which they will be successful. More specifically, topics range from consumer preferences and battery technology development to geo-political issues. Consumers were found to be quite pragmatic in relation to EVs (Caulfield et al., 2010; Lane and Potter, 2007) Even though consumers express a high level of concern for environmental issues, their behavior is still largely driven by issues such as vehicle cost, fuel price and safety. This is unfortunate for EVs because they are generally more expensive than comparable ICE vehicles and partially depend on environmental benefits to attract consumers (Gärling and Thøgersen, 2001). EV proponents commonly point to lower fuel costs as a way to attract customers. However, studies show that consumers incorrectly estimate lifetime gasoline costs and potential savings, resulting in them not making rational cost-benefit decisions (Turrentine and Kurani, 2007). This is referred to as the 'energy efficiency gap', which manifests by consumers selecting products that have lower purchase prices but higher lifetime costs (Brown, 2001; Levine et al., 1995). Fuel and other lifecycle savings must be notable within 2.5 years to be attractive to consumers (Kubik, 2006). This distorts the actual lifetime cost of EVs and discourages potential adopters.

²⁶ A complete list of abbreviations used in this study can be found in Appendix C.

The purchase cost of an electric vehicle is, to a great extent, driven by the battery. Battery price is commonly identified as the most important factor for the success of electric vehicles (IEA, 2011; Dijk and Yarime, 2010). Due to its importance, many automobile and battery manufacturers have elected to form joint ventures or partnerships in order to develop lithium-ion battery technology (Lowe et al., 2010). Recent developments in battery technology, specifically in lithium-ion battery chemistry, have reduced the cost per kilowatt hour, but ICE vehicles are still thousands of dollars cheaper than comparable EVs (Chan, 2007; IEA, 2009). Lithium-ion batteries for consumer electronics have decreased from ~\$1850 per kilowatt hour (kWh) in 1999 to ~\$500/kWh in 2006 (in 2011 dollars) (US DoE, 2007). Lithium-ion batteries for vehicles were estimated to be \$1000–\$1200/kWh in 2008 and \$700–\$950/kWh in 2011 (US DoE, 2011a). The expectation among analysts is as battery costs continue to decrease through technological and manufacturing improvements EVs will become attractive for a larger pool of customers (IEA, 2011). However, the timeframe for battery advances is ambiguous. Due to several factors, the lithium-ion battery market for electric vehicles is currently in a period of uncertainty. The lithium-ion battery market has seen a growing number of startup firms which has coincided with increased optimism regarding the future of EVs (Lowe et al., 2010). There is also an expanding variety of lithium-ion technology being developed by battery makers (IEA, 2011). However, because future demand for EVs and lithium-ion batteries is so unclear, manufacturers do not know what capacity levels should be. The result of the interplay between these dynamics of the battery industry will be influential in any future success of EVs.

Other factors that have aided in the resurgence in EV interest include regulatory pressure promoting low-emission vehicles, tax credits and high oil prices. Governments are passing laws that require car makers to produce vehicles with lower emissions levels. These new regulations are less stringent than the ZEV mandate and appear to be accepted by auto makers (Dyerson and Pilkington, 2005). The EU calls for a gradual lowering of manufacturer fleet average CO₂ emissions toward 130 g/km in 2015 and a 2020 target is set at 95 g/km (European Commission, 2009). The US has adopted the Californian Air Resources Board (CARB) CO₂ emission regulations and these are set at 156 g/km fleet average in 2016 (CARB, 2009; EPA, 2010).

A weakened ZEV mandate still encourages the production of vehicles without emissions. Manufacturers can also meet CARB emission requirements through low-emission vehicles such as HEVs. Current ZEV regulations are not as strict as the original mandate in the sense that they do not require production of zero-emission vehicles. It should be noted though that both in the EU and US, manufacturers can meet emissions level requirements faster through producing true ZEVs. Thus, there is still an incentive to innovate radically. The EU 2020 target of 95 g/km will be difficult to reach without ZEVs. Higher oil prices will also affect automobile consumers from a psychological and financial perspective and have been linked to higher sales of alternative fuel vehicles (Chanaron and Teske, 2007; Struben and Sterman, 2008).

Additional government policy measures to encourage adoption and development of electric vehicle technology have included tax credits and subsidies to consumers and low-interest loans and grants to firms (US DoE, 2009a; Spain, 2011; Tesla, 2009). These policies promote EV commercialization through supporting new companies (low-interest loans), advancing specific research efforts (grants) and making the price of EVs more appealing to customers (tax credits and subsidies). Of particular importance to our research effort is the literature that deals with the behavior of auto makers. Large manufacturers produced prototype and production EV models during the mid to late 1990s, but this was largely due to the ZEV

mandate. The low level of sales and amendment of the ZEV mandate eventually shifted R&D focus to other technologies such as HEV (Dijk and Yarime, 2010). From the mid 1990s to 2005, large incumbents have been diversifying their patent portfolio through development of low-emission vehicle technology such as electric (Oltra and Saint Jean, 2009) and hydrogen vehicles (Bakker, 2010a). Recent developments in limited leasing of EVs by large auto makers such as Mercedes, Mitsubishi and Nissan suggests, according to Magnusson and Berggren (2011), that the EV market is now viewed as a commercial opportunity instead of a regulatory requirement.

The research identified above, does not provide an understanding of the industrial dynamics during the recent development of EV models. It does not address the relation between the types of firms that have developed EVs, what specific technologies they have adopted and what markets they are targeting. For instance, in the literature there is a strong focus on the role of incumbents, while, as we will show, new-entry firms have developed just as many EV models and may play a pivotal role in the transition toward a large sustainable EV market.

The goal in this paper is to uncover the industrial dynamics during this early transitional phase and ultimately we aim to draw conclusions about the likelihood of EVs eventually becoming a legitimate competitor to ICE vehicles. This will be accomplished through examination of elements of the market environment in which EVs compete; specifically by identifying the types of firms that are producing EVs, the battery chemistries being used in EV models and the markets for which EV models are being designed. Within the market element of the study are four sub-questions. (1) What classifications of EV models are manufacturers producing? (2) What (if any) are the differences in the characteristics (class and performance) of vehicles made by incumbent and startup firms? (3) To what extent are firms making commercial or passenger vehicle models? (4) How do the performance characteristics of EV models compare to conventional ICE automobiles? Answering these questions will help to understand the scope of the current transition and whether EVs are being developed as an innovation to challenge the mainstream market dominance of the ICE vehicle or as a technology that will continue to compete in niche markets.

In this research we aim to generate insights in the type of markets that are most promising, from the perspective of the industry, for the next generation of EVs and, more fundamentally, on the industrial dynamics at work during a transition involving an eco-innovation. With respect to the latter, it is not only the promise that is presented by the electric vehicle itself that has triggered this era of ferment, but also the perceived need for cleaner and more efficient vehicles that threatens the current dominant design and creates a window of opportunity for alternative energy sources and powertrains.

4.2. Theory

Within technological innovation literature, the technology cycle model provides a number of insights into the dynamics of changing industries under the influence of (radical) innovations. One basic assumption in this literature is that radical innovations are initially inferior based on most existing performance standards (Adner, 2002). This leads to development of the innovation in niche markets where it is able to achieve a competitive advantage (Christensen, 1997). In the case of electric vehicles, the technology has advantages in terms of environmental performance, which is not necessarily beneficial to either producers or consumers but provides a positive externality for society. Therefore, we argue to analyze the current competitive environment of electric vehicles and the behavior of auto makers it is necessary to combine the technology cycle concept with an understanding of eco-innovations.

In this section we discuss both strands of literature and combine these to develop a framework for understanding both electric vehicles as a technology and industrial change via eco-innovations.

The technology cycle refers to a cyclical pattern of product development that is divided into two stages – an era of ferment and a period of incremental improvements. An era of ferment begins with the appearance of a technological breakthrough or discontinuity in the form of a competence-enhancing or competence-destroying innovation (Tushman and Anderson, 1986). A competence-enhancing innovation builds upon existing knowledge while competence-destroying innovations or disruptive innovations require a different set of engineering standards and opens up new market opportunities (Tushman and Anderson, 1986; Henderson and Clark, 1990; Christensen, 1997). EVs would be considered a competence-destroying innovation. Examples of successful disruptive innovations include 3.5-in. hard disk drives, jet engines and minicomputers (Bower and Christensen, 1995). Examples of unsuccessful radical innovations include Mini Discs, Apple's Newton and electric vehicles in the 1990s. Following the appearance of a technological discontinuity is a fluid phase where performance specifications are not well defined and innovation happens at a very rapid pace (Clark, 1985). This era of ferment ends when a dominant design captures a majority of the market and coincides with the establishment of technological standards and economies of scale (Abernathy, 1978; David and Greenstein, 1990). The emergence of a dominant design starts a period of incremental technological improvement that usually leads to a small number of firms controlling the market (Tushman and Anderson, 1986). The period of gradual improvement ends with the appearance of another technological discontinuity and the cycle begins anew (Tushman and Murmann, 1998; Utterback and Suárez, 1993).

One of the common patterns that characterize an era of ferment is the presence of a wide variety of technological approaches to the product innovation (Tushman and Anderson, 1986; Utterback and Abernathy, 1975). By developing different technological approaches to a product, firms are attempting to find the version of the innovation that is the most successful in the market. Throughout the era of ferment, producers are uncertain about which technology will best be able to meet the consumer demands and consumers are uncertain about the performance of the technology. In the early 1900s automobile era of ferment, vehicles powered by steam, battery or internal combustion engine competed against one another. The internal combustion engine eventually emerged as the dominant design, and the other technologies were relegated to the sidelines (Abernathy, 1978; Kirsch, 2000). This pattern of increase and decrease in technological variety during and after an era of ferment is common for disruptive innovations.

New products have low profit margins due to a lack of economies of scale and efficient manufacturing processes. Producer/consumer uncertainty and low profits coincide with low barriers to entry for firms during a technology's era of ferment (Clark, 1985; Van Dijk, 2000). One of the characteristics of a disruptive innovation is the entry of many firms (Klepper, 1996). This compares to a different situation with a mature technology where a few firms control a large portion of the market share and it is difficult for a new firm to enter the market (Van Dijk, 2000). Past research identified high numbers of competitors that entered the market during eras of ferment for industries such as automobiles, televisions and semi-conductors (Smith, 1968; Utterback and Suárez, 1993).

Incumbents and startup firms have historically employed different approaches toward disruptive innovations. In some instances startup firms have been able to displace large incumbents. In other instances large incumbents have successfully adapted to the introduction

of a new innovation and maintained their market share (Foster, 1986). Startup firms almost always bring a discontinuous technology to an industry (Tushman and Anderson, 1986; Utterback, 1994). However, the emerging dominant design generally results from the combined efforts of newcomer and incumbent firms (Anderson and Tushman, 1990). An incumbent firm's perception of a technology is largely framed by current customer demands and the company's previous experience with said technology (Cohen and Leventhal, 1990). Because of this framing, incumbents often are unsuccessful in addressing the emergence of a new technology and approach an innovation in a way that more closely resembles the conventionally used product or process. Incumbent companies are more concerned with satisfying the immediate needs of their customers than devoting resources toward technologies that are not being currently demanded and for which there is a small profit margin. In previous instances of disruptive innovations (e.g. mini-computers), incumbents did not recognize or invest resources in technology which led to them losing market share to startup firms (Bower and Christensen, 1995).

Lastly, disruptive innovations in their early stages of development typically compare poorly with incumbent technologies in terms of price and social conceptions of how the technology should perform (Adner, 2002). For this reason they first compete in niche markets where their performance limitations are minimized. An example of this is the 3.5-in. hard drive disc that was initially used in the niche market of notebook computers even though it offered lower storage space than the 5.25-in. hard drive (Bower and Christensen, 1995). There is some evidence that EVs already compete in market niches which naturally align with the innovation's features and capabilities, e.g. city cars and sports cars (Van Bree et al., 2010). City cars are small vehicles with low top speeds that are designed for short trips and urban travel. Environmental impact is one performance category where EVs have an advantage over ICE vehicles. This attracts consumers that place a high value on the environment (Lane and Potter, 2007).

Eco-innovations differ from other types of innovations in that they provide a reduced environmental impact when compared to existing technological alternatives (Rennings, 2000). They are developed on the basis of their environmental friendliness rather than solely on their fitness with current price and performance criteria (Faber and Frenken, 2009). As a result, their reduced environmental impact often comes at higher costs to consumers or with lower (conventional) performance levels (Janssen and Jager, 2002). Despite their drawbacks, eco-innovations such as photovoltaic cells, compact fluorescent lamps and hybrid-electric vehicles have been successfully introduced (to a greater or lesser extent) in the market.

Three factors that have played an important role in the early success of those products are consumer preferences, product energy efficiency and government regulation. Important early adopters of eco-innovations known as eco-consumers prefer and are often willing to pay a premium for environmentally friendly products (Jay, 1990). However, these individuals make up a small portion of automobile consumers as vehicle cost is still the most important criterion for the vast majority of the auto buyers (Caulfield et al., 2010). Additionally, many eco-innovations are energy-saving products that typically have lower operating costs than conventional alternatives. A re-examination of the product cost calculation regarding the frequent high purchase cost and low operating costs of eco-innovations (Brown, 2001) can potentially shed a different light on their price/performance characteristics. Companies are more likely than households to calculate these costs correctly and in the situation where an eco-innovation offers lower lifetime costs when compared to the standard technology (e.g. compact fluorescent lamps vs. incandescent bulbs), companies have adopted the product earlier than households (Menanteau and Lefebvre, 2000; US DoE, 2009b). Lastly, eco-

innovations are often supported or through government regulation. Governments have used various policies to encourage their adoption such as grants to manufacturers, subsidies to consumers and mandating their production.

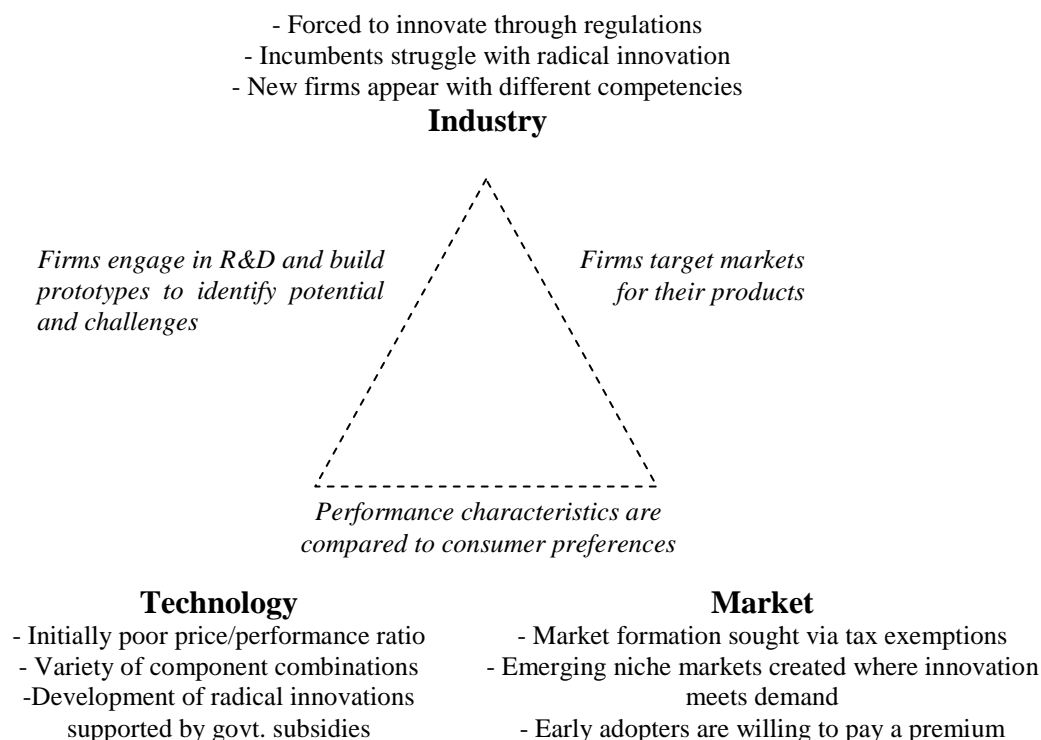


Figure 4-1: Research framework for eco-innovations during an era of ferment

Most radical innovation trajectories face poor price/performance characteristics during their early phases. This is especially true for eco-innovations. While ‘regular’ radical innovations are developed with the hope or expectation that they will eventually outperform conventional technology, eco-innovations are developed under different circumstances including pressure from government regulation, possible disruptive changes in socio-technical landscapes (e.g. depletion of oil supplies) and radical shifts in consumer preferences.

Due to their unique characteristics and the ways in which they are influenced by government policies, the technology cycle probably functions differently during the development of eco-innovations. Distinct dynamics can be expected to emerge as the industry structure changes, firms struggle to find optimal component configurations and the market takes shape (e.g. evolving selection criteria). Figure 4-1 depicts this relationship in the technology cycle for eco-innovations and we have sketched expected characteristics of and dynamics between each fundamental element. Existing firms in the industry are forced to innovate and often struggle with the new technologies, while new entrants may be better equipped to take advantage of an innovation’s new capabilities. The technology itself is unarticulated and initially performs poorly relative to conventional products. The market is, despite some supportive governmental measures, limited to niches and eco-enthusiastic early adaptors. As a result, all three elements contribute to a high level of uncertainty. It is not clear which firms or technological designs will eventually succeed or what the market will look like for the new products. Governments attempt to influence these industrial dynamics through approaches

such as tax exemptions for early consumers, subsidies to firms and minimum performance requirements (e.g. emissions regulation).

This paper aims to uncover these dynamics in the case of the automotive industry and electric vehicles. We do so through an analysis of prototype and production electric vehicles that firms have developed. This analysis unveils the types of firms, technological articulations and targeted markets that have emerged in the recent period of uncertainty regarding of electric vehicle production.

4.3. Methodology

Given the early phase of EV commercialization, we have opted for an analysis on the basis of prototype and early production models instead of actual sales figures. EV sales numbers are low and would give a strong bias toward the early movers, while our dataset provides insight into early commercialization and pre-production activity by manufacturers. The data we use in our study consists of a unique set of electric vehicle prototype and production models from 1991 to 2011. This research deals with vehicles that exclusively use electricity as fuel. Thus, hydrogen fuel-cell vehicles and plug-in HEVs are not included in the dataset. As a frame of reference for the demand side of the market, Table 4-1 provides an overview of the percent of EVs that were sold, leased or converted relative to all vehicle sales in the US from 1999 to 2008. It shows that EV sales data are too scarce to provide a robust analysis of the current market environment.

Table 4-1: Electric vehicles that were sold, leased or converted as a proportion of all vehicle sales in the US from 1999 to 2008 (US DoE, 2011b)

1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
0.01%	0.04%	0.05%	0.10%	0.08%	0.01%	0.02%	0.02%	0.02%	0.03%

Multiple sources were used to gather EV model data with government reports, professional websites and auto shows providing a majority of the vehicle information. The characteristics of specific EV models were confirmed through mainstream newspaper articles, company press releases or personal contact with the manufacturer. This method was specifically chosen because it provides up-to-date information about a rapidly changing technological landscape. Data for EV models include the following: manufacturer, driving range, top speed, date presented to the public, classification, company type, and battery chemistry. These data categories are incorporated in the analytical framework in Section 4.2 as follows: industry (company type), market (classification, driving range and top speed) and technology (driving range, top speed, and battery chemistry). Most of this information was gathered directly from a press release or government report, but data for ‘company type’ were interpreted based on other criteria.

For each EV model, companies were divided into one of four categories – large incumbent, small incumbent, startup or diversifying firm. The technology cycle literature specifically distinguishes between incumbents, startups and diversifying firms. This study chose to distinguish between large and small incumbents because there is such a disparity in resources between the two types of firms. This disparity in resources might lead to different approaches toward EV development. Large incumbents were defined as having sold automobiles before 1991 and being one of the 30 largest vehicle manufacturers in the world based on the 2009 International Organization of Motor Vehicle manufacturers production figures (OICA, 2010). Those 30 manufacturers accounted for 95% of global vehicle production in 2009. Small incumbents were defined as having sold automobiles before 1991 and not being one of the 30

largest manufacturers in 2009. Startup companies were defined as not having sold automobiles before 1991. Diversifying companies existed before 1991, but were not involved in the sale of vehicles, representing such industries as energy storage and engineering.

EV models were classified according the German Federal Transport Authority (KBA) automobile classification system: mini, small, compact, upper-medium, executive, sports car, luxury, multipurpose (MPV), sports utility (SUV), light commercial (LCV), heavy commercial (HCV), and bus (KBA, 2009). Distinguishing criteria and examples of these vehicle classes are provided in Tables 4-2 and 4-3. In addition, the categories of LSVs and 3-wheelers were also included because of their prevalence among EV models.

Table 4-2: Vehicle classification scheme (SMMT, 2009)

	Engine Size	Vehicle Length	ICE example	EV example
Mini	~ 1.0 L	< 3050 mm	Smart ForTwo	Tezzari Zero
Small	~ 1.0 – 1.4 L	< 3745 mm	VW Polo	BMW Mini E
Compact	~ 1.3 - 2.0 L	< 4230 mm	VW Golf	Volvo C30 EV
Upper-medium	~ 1.6 - 2.8 L	< 4470 mm	VW Passat	Nissan Leaf
Executive	~ 2.0 - 3.5 L	< 4800 mm	Daimler	BYD Auto e6
Luxury	> 3.5 L	N/A	Cadillac CTS	Rolls Royce 102

Table 4-3: Vehicle classification scheme (ACEA, 2009; SMMT, 2009, 2011)

	Descriptive Criteria	ICE Example	EV Example
LSV (quadricycle)	Lower safety standards	Bellier XLD	GEM eL
3-wheeler	Vehicle with 3 wheels	GM Lean Machine	Aptera 2e
Sports car	High performance	Porsche Boxter	Venturi Fetish
MPV	Seats up to 8 persons	Dodge Caravan	Ford Transit
SUV	4X4 off road	Ford Escape	Toyota Rav4 EV
LCV	<= 3.5 tons	Jeep Wrangler	E-wolf Omega 1.4
HCV	> 3.5 tons	Freightliner	Balqon Nautilus E20
Bus	Can carry > 10 persons	Champion	Tecnobus Gulliver

If a vehicle had two battery types, e.g. lead-acid and lithium-ion, then it was counted as two vehicle models. Other changes to a vehicle did not classify it as a separate model. In an instance where a vehicle had a prototype and production version, the characteristics of the production version were collected and used in the final analysis. For companies such as PSA which sell the same vehicle under multiple brands, only one version was included, e.g. Peugeot iGo and Citroen C-zero.

The luxury vehicle class was not used when analyzing EV models because luxury vehicles can occupy any passenger vehicle classification as long as it fits some cost threshold. That threshold is somewhat arbitrary and often part of a marketing strategy. EV prototypes do not have an associated purchase price, and many of the production vehicles are expensive and would constitute luxury vehicles.

This research uses cross-sections of different categories of information within the data set in order to better understand the competitive environment of electric vehicles. In doing this, two era of ferment patterns are analyzed; increased firm entry rate and expansion in the variety of technological approaches to the innovation. The number and type of manufacturers that presented a functional EV model to the public are plotted yearly over the study period in order to gauge firm entry rate. The chemistries of EV batteries are plotted from 1991 to 2011

to ascertain the change in technology variety. This analysis notes the roles of incumbent and startup firms in the development of EV models.

In order to gauge what type of vehicles might appear in the early adopter phase, models are grouped according to vehicle classification and manufacturer type. The goal of this analysis is to provide insight into manufacturer strategies regarding the developing industry, e.g. in which vehicle classes they expect EVs to be competitive. The 2008 annual vehicle sales from Germany and the UK provide some perspective as to which classes of automobiles are commonly purchased by consumers. Those two countries were selected because they are both large economies with one country (Germany) having large domestic automobile production (1.847 vehicle production to registration ratio) and the other (UK) with lower domestic automobile production (0.607 vehicle production to registration ratio) (ACEA, 2011a,b). Comparing annual vehicle sales to number of EV models produced helps to highlight where manufacturers expect niche markets to exist in comparison with current customer demand. Examining EV models according to manufacturer type and top speed provides further clarification of the performance characteristics (top speed) manufacturers produce as well as insight into incumbent and startup firm strategies.

A prototype and production model analysis was chosen over other alternatives such as a patent analysis for several reasons. Patent analyses provide a different indication of technological development than the analysis of prototype and production models. Developing a prototype is an expensive and time consuming endeavor and requires a certain level of commitment to that vehicle's technology from the manufacturer. Additionally, an extensive analysis of the prototype and production EV models developed by car makers does not exist. Previous EV studies have looked at only a small portion of the vehicles that have been developed over the past two decades. Prototype or production vehicles developed by auto manufacturers can be used to determine their attention toward the EV market. Lastly, a prototype and production model analysis is useful to gain insight into an industry in situations where there are low sales and a large number of manufacturers such as the case of an emerging technology (Bakker et al., 2012).

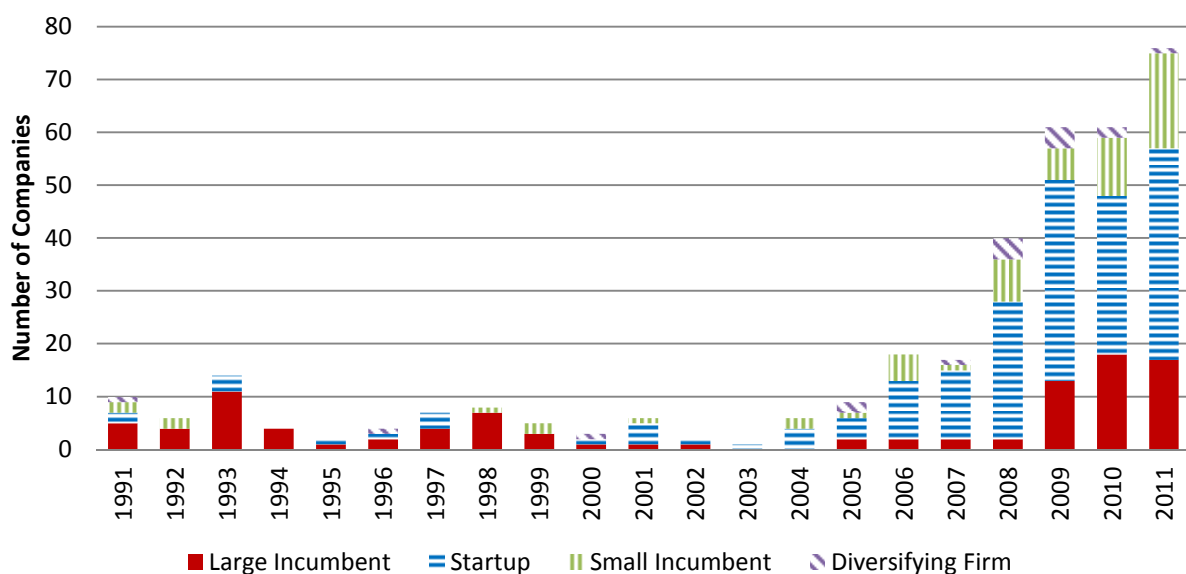


Figure 4-2: Companies producing electric vehicles

4.4. Results and discussion

During a technology's era of ferment there are low barriers to entry leading to an increased number of competing firms. Figure 4-2 shows how many companies have produced EV models from 1991 to 2011. The number of companies producing EV models in a given year fluctuated between two and 14 until the middle of the 2000s. Up to that point, EV models were principally produced by large incumbent manufacturers.

The number of companies that manufactured an EV model increased from one in 2003 to 76 in 2011 with startup firms composing a majority of the growth during that time period. This increase in manufacturers was larger than during the last attempt at broad commercialization of EVs during the 1990s, which indicates that the industrial dynamics are different in the current situation. Small incumbents and diversifying firms were largely absent from EV production until 2008 but have produced at least 10 models per year since then. The presence of a large number of competing startup firms distinguishes EVs from other powertrain alternatives (biofuel, natural gas, hydrogen, or hybrid-electric), which are manufactured almost without exception by large incumbent corporations or publicly funded research institutions. Figure 4-2 shows that large incumbents are investing in electric vehicle technology and have been actively developing new models throughout the study period. This suggests that incumbents recognize the transformative potential of EVs and do not want to miss out on a potential paradigm shift in the automobile industry.

The technology cycle literature tells us that as a new innovation emerges, the number of different technological approaches to the product or process is expected to increase. Technological variety is measured in this study by looking at the battery chemistry being used by electric vehicle models. The chemistry of rechargeable batteries is composed of a positive terminal (anode), negative terminal (cathode) and an electrolyte that allows ions to pass between the two charged sections. The electrolyte is contained in either an organic solvent or polymer composite. Battery companies have developed different substances for use as cathodes, anodes and electrolytes in an attempt to garner better battery performance (Besenhard, 1999). Battery chemistries for electric vehicles are largely grouped into four families: lead-acid, nickel-based, lithium-based and sodium-nickel-chloride (zebra).

Figure 4-3 shows the number of unique battery chemistries used in EV models from 1991 to 2011. This number fluctuated between two and five during the 1990s and decreased to two or one during the first half of the 2000s (which coincided with high interest in hydrogen fuel-cell technology) (Bakker, 2010b). The number of different chemistries in EV models increased from one in 2005 to 13 in 2010 and 10 in 2011. Battery technology changed from being nickel-based during the 1990s to lithium-based in the 2000s with lead-acid batteries constantly used in EV models throughout the study period. Zebra batteries appeared in vehicles in the early 1990s and reappeared in the mid to late 2000s. The fate of zebra batteries seems to be largely tied to one company (MES-DEA later known as FZ Sonick) which produces practically all EV models that use that particular battery chemistry. There were some vehicles with lithium batteries in the 1990s, but these were largely prototypes and did not immediately lead to production EVs. The majority of the models (particularly those in production) developed during the 1990s used either lead-acid or nickel-based batteries. Lithium-cobalt batteries first appeared in 1995 with lithium-manganese batteries following in 1999.

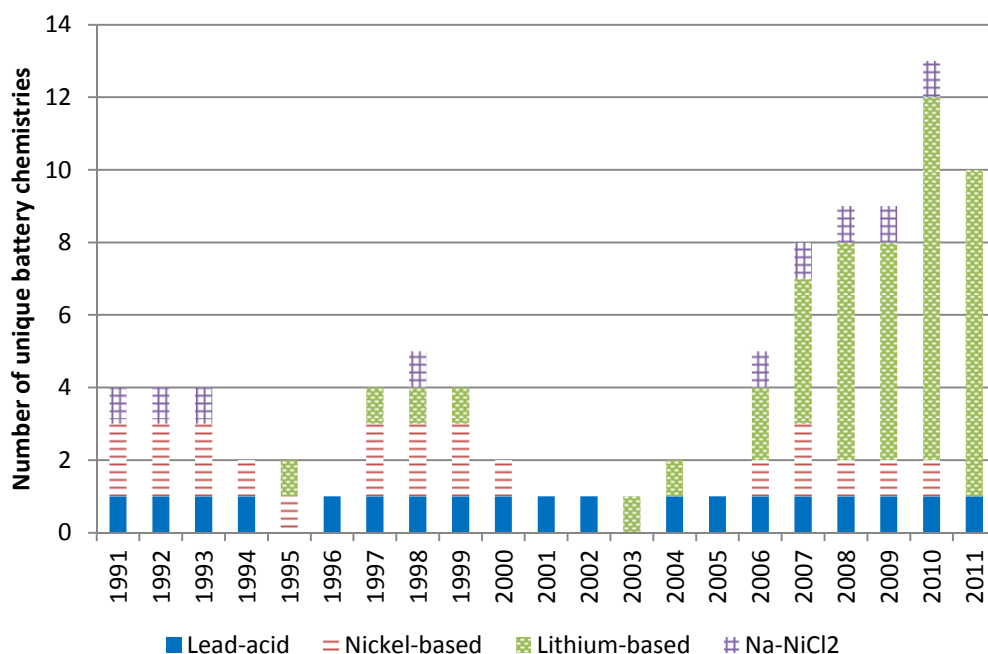


Figure 4-3: Unique battery chemistries in electric vehicle models

Toward the end of the 2000s, more EV models were using lithium-iron-phosphate batteries than any other chemistry. Recent expansions in technology variety have included the use of nickel and vanadium in lithium batteries. In addition to anode and cathode materials, there have also been attempts to employ different approaches toward electrolytes. Most lithium batteries utilized organic salts in the electrolyte although the number of lithium-ion polymer batteries increased during the latter end of the study period. Table 4-4 shows a breakdown of the lithium-ion battery chemistries that were used in EV models from the data set.

Table 4-4: Lithium-ion battery chemistries

Cathode	Anode	Electrolyte
LiCoO_2	LiC_6	Org. Solvent
LiFeMnPO_4	LiC_6	Org. Solvent
LiFePO_4	LiC_6	Org. Solvent
$\text{LiMn}_2\text{CoO}_4$	LiC_6	Org. Solvent
LiMn_2O_4	LiC_6	Org. Solvent
LiMn_2O_4	LiC_6	Poly. Composite
LiMn_2O_4	$\text{Li}_4\text{Ti}_5\text{O}_{12}$	Org. Solvent
$\text{Li}(\text{NiCoAl})\text{O}_2$	LiC_6	Org. Solvent
$\text{Li}(\text{NiMnCo})\text{O}_2$	LiC_6	Org. Solvent
$\text{Li}(\text{NiMnCo})\text{O}_2$	LiC_6	Poly. Composite
$\text{Li}_3\text{V}_2(\text{PO}_4)_3$	LiC_6	Org. Solvent
$\text{Li}_3\text{V}_2(\text{PO}_4)_3$	LiC_6	Poly. Composite

The period of 2008–2011 saw an increase in the number of EV models using lithium batteries and a decrease in the use of all other battery chemistries. This indicates that EV manufacturers have determined that lithium batteries represent the best opportunity for EVs to be competitive in the automobile industry. EVs using lead-acid batteries provide a good example of this trend. Throughout the study period, new EV models that used lead-acid

batteries appeared every year but one (2003). These models generally fall into the LSV class, examples of which include golf carts and recreational vehicles. However, LSV with lithium-ion batteries started appearing more frequently in 2009. This indicates that lithium batteries are having an impact in an EV market that has traditionally employed lead-acid batteries.

Based on the number of firms producing EV models, the emergence of startup firms and the expansion in technological variety, it appears that an increase in activity relating to electric vehicles began in roughly 2004. Whether this is an era of ferment will depend on whether EVs take over a majority of the automobile market from ICE technology and cannot be determined until a future date when an ex post analysis can be performed. In either case, this time period represents an era that deserves additional investigation. The remainder of Section 4.4 will focus on EV models from 2004 to 2011.

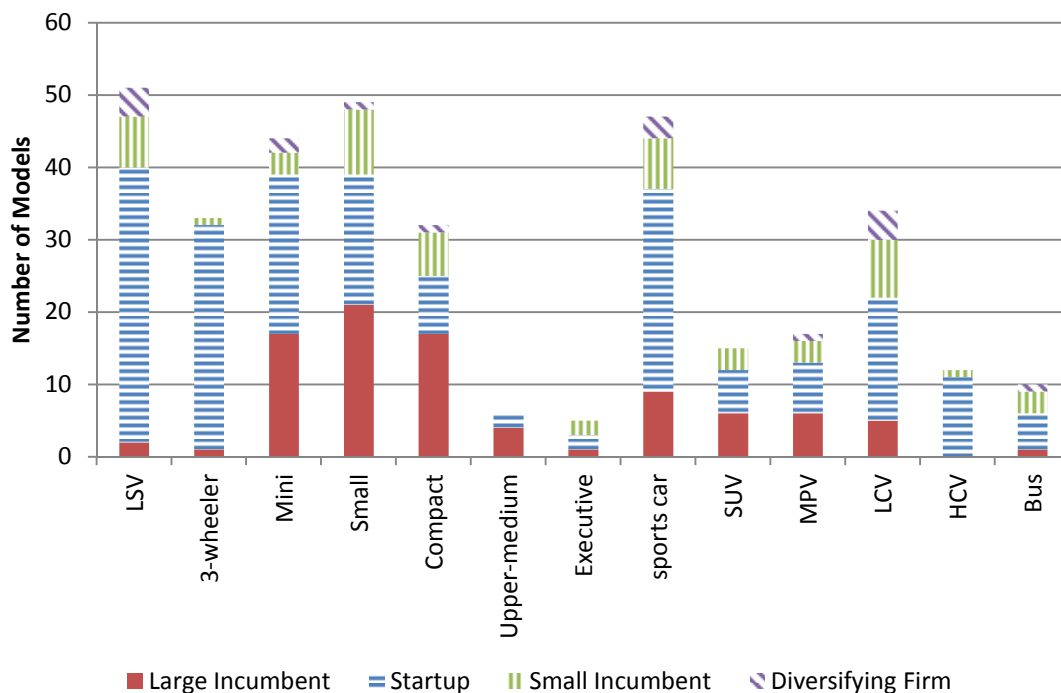


Figure 4-4: Electric vehicle classification by manufacturer type

Figures 4-3 and 4-4 break down the EV models produced by manufacturers between 2004 and 2011 into vehicle classes. The most commonly produced models were LSV (51), small (49), sports cars (47) and mini (44). There were also more than 25 models in the following vehicle classes: 3-wheeler, compact and LCV. There were few models developed in large passenger vehicle classes of upper-medium and executive.

Commercial adoption of electric vehicles represents a potentially different use of the technology, e.g. more intensive use with taxi or goods transportation services. Eco-innovations such as the compact fluorescent lamp (CFL) have been adopted by companies before households (Menanteau and Lefebvre, 2000; US DoE, 2009b). This leads one to expect that manufacturers might initially develop a large number of LCV, bus or HCV models in anticipation of commercial vehicles being one of the first available markets. LCV represented the 5th largest class of models produced during the study period. It is possible that some of the passenger EV models were also developed with a commercial use in mind (e.g. taxis).

While commercial vehicles did constitute a class with one of the larger number of models produced, the data do not suggest that manufacturers specifically targeted the commercial EV market before the household EV market. It is worth noting that CFLs that were adopted by businesses offered lower lifetime costs than incandescent lamps. Currently an EV, even with lower fuel costs, still has a higher lifetime cost than a comparable ICE vehicle. So it is unlikely that EVs provide as attractive a value proposition as CFLs did when they were first adopted by business customers.

Large incumbents and startups had different approaches toward EV production. Large incumbents developed a number of models in the mini, small, compact, and sports car classes. They avoided unconventional vehicles such as 3-wheelers and LSV and large commercial vehicles (buses and HCV). Perhaps large incumbents avoided producing unconventional vehicles like LSV or 3-wheelers because they differ markedly from current customer automobile demand. It is common for incumbents to be more concerned with fulfilling the needs of their current customers than identifying the customer needs of an emerging technology. Startups developed EVs in all vehicle classes while specifically focusing on models at the top and bottom of the market with 3-wheelers, LSV, and sports cars. Larger passenger vehicles such as compact, upper-medium, executive, SUV and MPV accounted for a relatively small proportion of the models produced by startups.

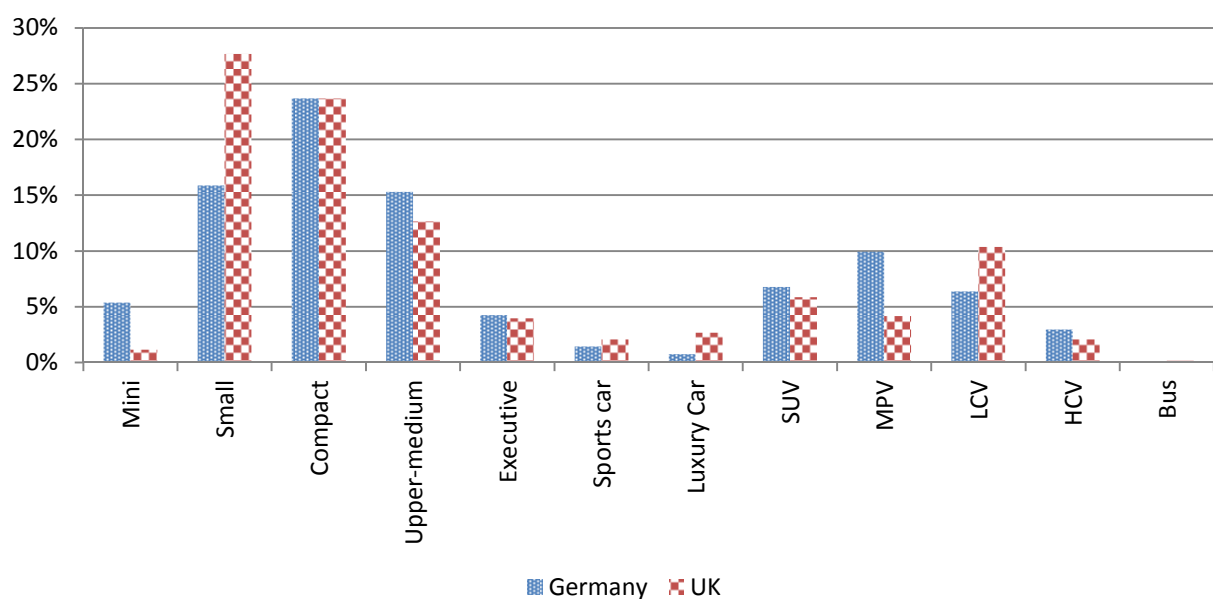


Figure 4-5: 2008 German and United Kingdom new car registrations

Sports cars are a reasonable market for EVs due to their higher price and performance features. EVs can achieve maximum torque as soon as the accelerator is depressed as opposed to ICE vehicles which gradually achieve maximum torque. Sports cars allow manufacturers to focus on the performance capabilities of EVs while decreasing the importance of high vehicle cost. The mini class of automobiles also makes for a predictable EV market because it is more likely to consist of light-weight city cars that do not need to have a high top speed or long driving range. The high number of LSV and 3-wheelers fits into a common niche market approach as firms explore potential markets for emerging innovations. There were very few EVs made in the upper-medium class, even though it represented the 3rd most popular classification for consumers in Figure 4-5. This could be because large passenger vehicles highlight performance weaknesses of EVs, e.g. low driving range and EVs would not be competitive in that market.

Figure 4-5 presents the 2008 vehicle sales from Germany and the UK (ACEA, 2009; KBA, 2009; SMMT, 2009). The popular vehicle classes of small, compact and upper-medium comprised 55% and 64% of sales in Germany and the UK respectively. From a manufacturer's perspective, these classes encompass the largest automobile markets by volume. The other vehicle classes each represent approximately 10% or less of vehicle sales with several classes (HCV, bus, executive, sports car and luxury car) corresponding to less than 5% of sales. Extensive statistics for LSV registrations could not be identified, but a 2008 Canadian report estimated annual sales figures in Europe to be approximately 30,000 vehicles which would represent 0.2% of 2007 new car registrations in Europe (ITAQ, 2008; ACEA, 2011b).

Comparing Figures 4-4 and 4-5 helps to highlight the differences between consumer purchasing behavior toward ICE vehicles and the strategies employed by EV manufacturers. The figures also give some indication as to whether EV manufacturers are targeting niche or mass markets. Four of the vehicle classifications in Figure 4-4 (LSV, sports cars, 3-wheelers and mini) accounted for 49% of all EV models produced from 2004 to 2011. In Figure 4-5, those vehicle classes accounted for a small proportion of 2008 vehicle sales (6.9% in Germany and 3.3% in the UK). Based on those figures, EV manufacturers are producing a large proportion of their models for vehicle classifications that account for a small percentage of annual sales. This suggests that manufacturers are targeting minor markets in the case of mini vehicles and sports cars and niche markets in the cases of 3-wheelers and LSV. Startups developed EVs in all vehicle classes while specifically focusing on the niche markets of 3-wheelers and LSV and the minor market of sports cars. Mini, small and LCV were the vehicle classes that had the highest number of vehicle sales in which startups also manufactured a proportionally large number of EV models. Startup firms produced most of the commercial vehicle models, which could indicate intent by some new companies to specifically target the commercial market. In addition to the mini class, large incumbents concentrated on the two classes (small and compact) that accounted for the most vehicle sales in 2008 in Germany and the UK. This approach allows them to apply existing experience and expertise from ICE vehicles to EVs.

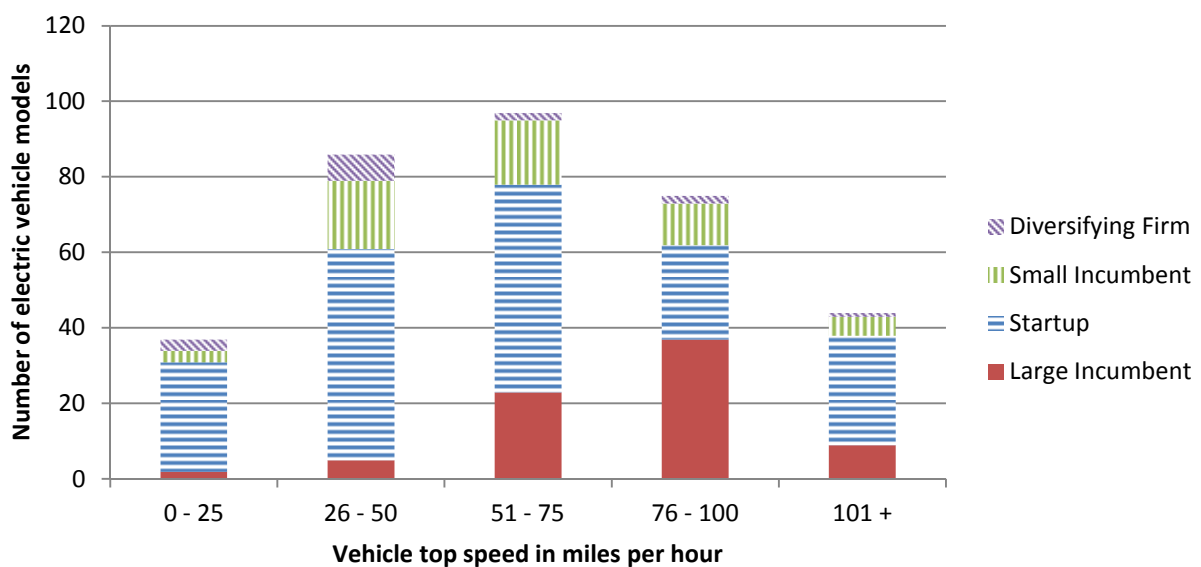


Figure 4-6: Electric vehicles by top speed and manufacturer type

This approach belies the expectation that early EVs will be similar to contemporary ICE vehicles, but powered by a battery instead of petrol. The high number of EV models developed by large incumbents in the mini class does indicate that they consider a shift in the size and shape of future automobiles to be possible. Small incumbents developed a number of models in all classes except upper-medium (where they developed zero models). Unlike large incumbents or startups, small incumbents did not appear to target any particular class of vehicle. Diversifying firms developed a small number of EV models in eight different classes. There does not appear to be a pattern to their approach.

Figure 4-6 breaks down the EV models from 2004 to 2011 according to top speed and manufacturer type. It shows that 36% of the EV models produced had top speeds below 50 miles per hour (mph). This is noteworthy considering that virtually all ICE vehicles have top speeds above 50 mph. For comparison, the average US vehicle top speed in 2007 was 139 mph (US DoE, 2008). Low top speeds would limit some EVs from driving on interstate highways, lending support to the idea that some of the early adopters will use EVs primarily as city cars. LSVs accounted for 41% of the vehicles with a top speed of 50 mph or less. The classes of LCV and mini composed 11% and 10% of the vehicle models with a top speed of 50 mph or less. The vehicles on the margins in Figure 4-6 (0–25 mph and 101+ mph) are almost entirely produced by startups and generally represent the LSV and sports car markets.

Startup firms developed vehicles in all speed categories while they dominated production in the 0–25 mph, 26–50 mph and 101+ mph groups. The EV models developed by startup firms largely fit into niche or small markets, e.g. LSV, sports cars and city cars. Large incumbents on the other hand primarily produced EV models with performance more similar to standard ICE vehicles, e.g. the 51–76 mph and 76–100 mph categories. Large incumbents developed few models in the markets of sports cars (high top speeds) and LSV (low top speeds). Small incumbents developed EV models in all speed categories, but generally focused on vehicles with speeds between 26 and 100 mph. Their development of vehicle with lower top speeds (26–50 mph) could indicate that they are targeting the city car market and not trying to compete directly with conventional ICE automobiles.

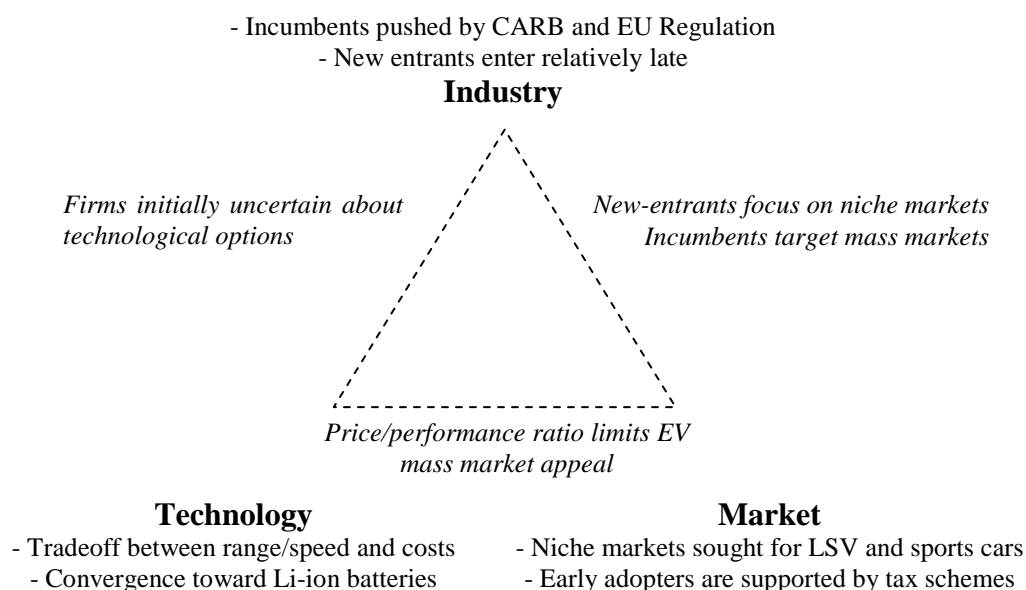


Figure 4-7: Conclusions represented in the analytical framework

4.5. Conclusion

When looking at the industrial dynamics of firms, markets and technologies, it appears that the electric vehicle industry is indeed displaying many of the characteristics seen during a transitional era of ferment including an increase in the entry of new firms, an expansion in technological variety (battery chemistries) and exploration of niche markets. Figure 4-7 identifies these and other results relative to the analytical framework outlined in Section 4.2. In 2003, one auto manufacturer produced an EV model. This number increased to 76 in 2011, with a majority being startup firms. In terms of the batteries found in EVs, manufacturers moved away from a small number of nickel-based chemistries to a much broader variety of lithium-based chemistries, with lead-acid batteries remaining prominent in low-speed vehicles. Regarding the markets targeted with EVs, our study reveals two significant results. The first is the industry's focus on smaller classes of passenger vehicles (mini and small) and niche vehicles (LSV and sports cars). With the exception of the 'small' class, these are not representative of popular consumer vehicle segments. Second, large incumbent firms primarily developed EVs with performance and size similar to current mass marketed automobiles. Startup firms developed EV models in all classes and performance ranges. However, true niche vehicles such as sports cars and LSV were much more likely to be made by a startup than an incumbent.

These findings can be explained by looking at the markets that firms targeted. Compared to ICE automobiles, EVs are relatively expensive and/or limited in terms of speed and range. Many of the EV models developed by startups largely targeted the small or low-speed market although consumer demand for those types of vehicles has been minimal. Thus, the market segments targeted by startups were not popular consumer automobile segments. In the sports car segment, price is less of an issue and in the other segments range and speed are of less importance. Startups targeted these markets because they offer comparative advantages to ICE vehicles and allow for low production volumes. Incumbents on the other hand are more concerned with high volume production and subsequently with the more conventional and popular vehicle segments, e.g. larger with better performance.

On a more speculative note, we expect a broader transition to commercialized EVs to happen first in niche markets. In the more conventional segments of the automobile market EVs are currently offered in small production series, but these are not likely to be profitable in the short term. Some companies may sell vehicles in those markets, but they are likely to be for a loss. Our data suggests that EV industrial dynamics are much more promising in the 2010s than they were during the surge in development during 1990s.

To be more specific, if the trends identified in this research continue, we anticipate the next several years to see increased commercial EV activity in two general markets. The first is specialty vehicles such as LSV and expensive sport cars. Many of the models that startups developed are in those vehicle classes, which positions new firms well for the EV early adoption stage. The second expected EV market is smaller city cars with limited performance targeted toward consumers whose mobility needs are limited and who are willing to pay a premium for eco-innovations. Large incumbents' EV models, which are more in line with current customer demand of ICE vehicles, will need cost reductions of the batteries to make this market viable. If successful in that respect, there is likely to be a strong uptake first among business customers and later the broader public.

There are several policy implications from this research. Policy makers should understand that battery development will continue regardless of the success of electric vehicles.

However, electric vehicles represent a way to support and speed up that process by expanding a market which requires advanced batteries. This research identifies to policy makers that auto manufacturers are seriously pursuing electric vehicles, which as a technology represents a viable way to achieve lower emissions, fuel independence and new economic opportunities. Governments have historically used different tools such as grants and subsidies to support EVs because of their potential economic and environmental benefits. It is not the purpose of this research to identify which policy instruments will be most effective at stimulating EV adoption. Rather it identifies the state of the market for policy makers, showing the viability of the EV industry and specifically what niche markets auto manufacturers are targeting with their models. That information can help law makers craft effective policies to promote the EV industry. Protecting key markets through tools such as emissions requirements, rebates and inclusion in government fleets encourages the continued development and commercialization of electric vehicles. Without protected niche markets, there will be limited opportunities for EV commercialization and the technology will develop at a slower rate. If there is little demand for EVs, it is possible that auto manufacturers could shift their research and development resources to different powertrain technologies.

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5. Government policy and electric vehicle adoption

Sierzchula, W., S. Bakker, K. Maat, and B. van Wee (2012) The influence of financial incentives and other socio-economic factors on electric vehicle adoption, in: *Energy Policy*, 68, 183-194.²⁷

Abstract

Electric vehicles represent an innovation with the potential to lower greenhouse gas emissions and help mitigate the causes of climate change. However, externalities including the appropriability of knowledge and pollution abatement result in societal/economic benefits that are not incorporated in electric vehicle prices. In order to address resulting market failures, governments have employed a number of policies. We seek to determine the relationship of one such policy instrument (consumer financial incentives) to electric vehicle adoption. Based on existing literature, we identified several additional socio-economic factors that are expected to be influential in determining electric vehicle adoption rates. Using multiple linear regression analysis, we examined the relationship between those variables and 30 national electric vehicle market shares for the year 2012. The model found financial incentives, charging infrastructure, and local presence of production facilities to be significant and positively correlated to a country's electric vehicle market share. Results suggest that of those factors, charging infrastructure was most strongly related to electric vehicle adoption. However, descriptive analysis suggests that neither financial incentives nor charging infrastructure ensure high electric vehicle adoption rates.

²⁷ Relative to the journal article version, years were added to the titles of Figures 5-2 and 5-4.

5.1. Introduction

The IPCC (2012) noted that climate change caused by rising levels of greenhouse gases (GHGs) poses a serious threat to the physical and economic livelihoods of individuals around the globe and could negatively affect ecosystems by putting 20–30% of plant and animal species at an increasingly high risk of extinction.²⁸ GHGs such as CO₂ and N₂O primarily come from the burning of fossil fuels during activities including electricity production and operating internal combustion engines. In 2010, the transport sector accounted for 6.7 Gt of emitted CO₂ or 22% of the world's total (IEA, 2012a). Furthermore, global fuel demand for transportation is projected to grow approximately 40% by 2035 (IEA, 2012b). The IPCC noted the need to reduce GHG emissions (particularly in the energy and transport sectors) in order to avoid a 2.4–6.4 °C increase in 2090 temperatures relative to those from 1990 (IPCC, 2012).

Electric vehicles (EVs) are one possible innovation to help address the environmental concerns identified above. However, EV adoption is seen as being very limited without stimulation from external factors such as stringent emissions regulations, rising fuel prices, or financial incentives (Eppstein et al., 2011; Shafiei et al., 2012; IEA, 2013). Of those factors, consumer subsidies are specifically identified as being necessary for EVs to reach a mass market (Hidrue et al., 2011; Eppstein et al., 2011). Part of the reason that diffusion is expected to be so slow is that pollution abatement and knowledge appropriability²⁹ externalities reduce EV development and consumer adoption, leading to an inefficient allocation of goods and services known as a market failure (Rennings, 2000; Jaffe et al., 2005; Struben and Sterman, 2008). In the case of EVs, market failures distort their prices relative to ICEVs, which results in fewer electric automobiles being built by firms or bought by consumers. Consequently, the potential to address climate change through EV development and use is limited by externalities; neo-classical economics indicates that government policy should be employed to help correct for such situations (Rennings, 2000). Of these policy measures, demand side instruments such as consumer subsidies are viewed as being particularly important during the early commercialization period (IEA, 2013). However, based on previous studies, there are reasons to question how effective such financial incentives would be in encouraging EV adoption.

Firstly, the literature has presented conflicting results regarding the effect of consumer subsidies on hybrid-electric vehicle (HEV) adoption. While some studies have shown financial incentives to be positively correlated to HEV sales (Beresteanu and Li, 2011; Gallagher and Muehlegger, 2011), Diamond (2009) found that higher fuel prices, not consumer subsidies, were related to increased adoption. In addition, Zhang et al. (2013) identified only a very weak relationship between purchase subsidies and consumer willingness to buy EVs. Thus, factors other than financial incentives could be the primary drivers of EV adoption.

Secondly, due to the nature of radical innovation development (Tushman and Anderson, 1986), there may be reasons to suspect that consumers may not behave in the same fashion toward HEVs as they do toward EVs. Innovations that are further away technologically from

²⁸ This is posed by the IPCC with “medium confidence” under a situation where global temperatures are 2–3 °C above pre-industrial levels.

²⁹ Knowledge appropriability or “knowledge spillover” relates to the ability of a firm to benefit from technologies or expertise that it develops as opposed to other companies gaining from those advances without investing in the necessary R&D, e.g., reverse engineering a developed product. Knowledge spillover results in lower rates of innovation.

the dominant design are associated with greater levels of uncertainty (Anderson and Tushman, 1990). Consequently, since EVs represent a more radical technological departure from ICEVs than do HEVs (Sierzchula et al., 2012), they result in increased levels of uncertainty, specifically among consumers (Sovacool and Hirsh, 2009). This uncertainty affects a broad array of industrial dynamics including future profitability of a technology, government involvement, and willingness to pay (Arrow, 1966; Nelson and Winter, 1977; Jaffe et al., 2005); the more an innovation differs from the conventional technology, the less consumers are willing to pay for it. Thus, higher consumer uncertainty regarding EVs decreases the amount that individuals are willing to pay relative to HEVs, in effect reducing the utility of financial incentives relative to EV adoption. This makes it difficult to estimate the impacts of financial incentives on the adoption of a radical innovation with significantly different performance characteristics relative to the conventional technology, as is the case with EVs. Therefore, earlier studies analyzing HEV adoption may under-represent the impact that financial incentives have on EV purchases.

In addition, consumer subsidies may have little effect on EV sales uptake if buyers are uncomfortable with the technology (Egbue and Long, 2012), or do not see enough EVs in the fleet around them (a threshold effect) (Eppstein et al., 2011). Our paper aims to contribute to the literature by examining if and to what extent financial incentives and other socio-economic factors explain EV adoption.

5.2. Barriers limiting innovation

The literature has identified several obstacles which limit the diffusion of new technologies such as EVs. For example, knowledge spillover applies broadly to all innovations while pollution abatement and bounded rationality³⁰ are typically associated with limiting the development and adoption of environmental technologies (eco-innovations) (Jaffe et al., 2005; Rennings, 2000). These barriers, which limit EV diffusion by influencing both the manufacturers that produce the automobiles and the consumers that buy them, are described more comprehensively below.

5.2.1. General barriers

In studying the development of innovations, Arrow (1962) determined that in a capitalist system, firms will underinvest in research and development of new technologies. This is primarily due to uncertainty, but also because an innovation's public benefit (for which businesses receive little financial compensation) often outweighs its private value to the company. The externality, of "positive knowledge spillover", occurs when innovations provide valuable information to non-consumers (Horbach, 2008).

For example, firms are not always able to prevent competitors from gaining from their R&D efforts. The degree to which a firm is able to defend the profits of an innovation from competitor imitation is referred to as its appropriability (Teece, 1986). Because it is not possible for a firm to keep every element of a new technology secret, other companies can gain by learning from and in some cases stealing the work of the original innovating entity. Thus, due to knowledge spillovers, businesses are less likely to invest in the development of innovations that are easily copied (having low levels of appropriability) because they will not be able to reap all of the rewards from a successful new technology (Teece, 1986). Positive knowledge spillover influences the industrial landscape such that although firms do invest in

³⁰ The notion that an individual's decision making is influenced by the information that he/she has.

the research and development of new technologies, they do so at a lower level than would be expected based on the financial benefits that innovations provide.

In addition, emerging technologies face further barriers because they often compare poorly to existing dominant designs in important criteria such as price and performance (Adner, 2002). For that reason, the first individuals to adopt an emerging radical innovation are often willing to pay a premium or cope with subpar performance in order to have the latest technology (Rogers, 1995). The larger proportion of the population known as early/late majority adopters are much more risk adverse, and are not willing to purchase an innovation so different from the dominant design (Rogers, 1995). It is vital for radical technologies to attract a significant enough number of early adopters to develop a viable market niche (Geels, 2002). Thereafter, industrial forces such as learning by doing and scale economies can rapidly lower costs and improve performance (Foster, 1986; Christensen, 1997). In order for an innovation such as electric vehicles to have a significant environmental impact, it needs to be widely adopted (and have dramatically lower emissions levels compared to ICEVs). For that to happen, there must first be enough demand within the EV niche market that manufacturers continue to develop and sell the automobiles. Consequently, governments have employed financial incentives to help attract early EV adopters.

5.2.2. Barriers that reduce eco-innovation

Eco-innovations differ from other new products and services in that they provide a lower environmental impact than the conventional technology (Rennings, 2000). Examples range from incremental improvements to existing designs such as turbocharging in automobile engines to more radical technologies, like solar cells and wind turbines. The distinct nature of eco-innovations improves general social utility through lower pollution abatement levels. However, this externality also creates market failure, and ultimately limits their development and adoption (Jaffe et al., 2005).

Investments in eco-innovation are specifically disincentivized because benefits from lower pollution levels are not included in a product's price. The externality pollution functions such that that even though many societal members profit from eco-innovations through improved health (however marginally), firms are not able to charge those individuals for their gains. As a result, eco-innovations have lower adoption levels than if societal benefits from decreased pollution were included in product costs (Brown, 2001).

An additional barrier that has contributed to lower eco-innovation diffusion is bounded rationality, which can influence consumer valuation of a product's purchase price, operating expenses, and lifetime cost. Instead of using rational choices to maximize an individual's utility, individuals are aware of only a portion of the available options and thus act on imperfect information (Nelson and Winter, 1982). Thus, in place of calculating out the total cost of ownership of a product, consumers often rely on heuristics or rules of thumb to guide their purchasing behavior (Jaffe and Stavins, 1994; Schleich, 2009). This can lead an individual to place too much emphasis on the purchase price and not accurately value operating expenses (Levine et al., 1995). Because many eco-innovations have high purchase prices and low operating expenses, they have often experienced slow diffusion rates (Brown, 2001). Specifically regarding EVs, consumers looking to purchase alternative fuel vehicles do not accurately incorporate fuel economy in their vehicle purchase decisions, leading to irrational behavior (Turrentine and Kurani, 2007).

5.3. Factors influencing EV adoption

Because EVs were introduced to the broader consumer market only recently in 2010 (not including their temporary commercialization in the 1990s), there is little research that uses empirical data to analyze factors which affect adoption rates. Thus, much of our knowledge about such contributing elements comes from stated preference studies. However, because of a phenomenon known as the “attitude–action gap”, there is the concern that information from consumer surveys may have little relation to the purchase of low-emission vehicles (Lane and Potter, 2007). This raises the value of research that analyzes actual consumer actions (revealed preferences), such as that performed in our paper.

HEVs provide a good comparison basis for EVs (even though they are less of a radical innovation) because they have several of the same key elements including a battery and electric motor based powertrain and lower environmental impacts. As HEVs have been commercially available since the late 1990s, there are several studies that used revealed preference data to investigate factors that influenced consumer uptake for those automobiles. In the absence of similar research for EVs, we have incorporated in our model variables that were found to be significant drivers of HEV adoption in those articles e.g., education level, fuel price, and environmentalism (Lane and Potter, 2007; Diamond, 2009; Gallagher and Muehlegger, 2011). Based on the findings in HEV revealed preference research, EV survey studies, and theoretical articles, we have collected and categorized the factors that are assumed to determine the decision of whether or not to purchase an electric vehicle as belonging to the technology itself, the consumer, or the context.

The technology category comprises aspects of electric vehicles including battery costs and performance characteristics (driving range and charging time). EV purchase prices, which are heavily dependent on battery costs, have been identified as being the most significant obstacle to widespread EV diffusion (Brownstone et al., 2000). The IEA (2011) found that the purchase price of an EV with a 30 kWh battery (approx. 85 miles³¹ of driving range at 0.17 kWh/mile) would be \$10,000 (all financial amounts in this article should be read as US dollars) more than a comparable ICEV. Battery costs also have an impact on the driving range of an EV. An increase in the size of an EV's battery (in kWh) raises both its driving range and purchase cost. Therefore, although consumers are sensitive to a limited driving range (Lieven et al., 2011) that aspect must be balanced with its relation to vehicle battery costs. An additional factor which influences consumer adoption is vehicle charging time (Hidrué et al., 2011; Neubauer et al., 2012). Whereas most ICEVs are able to refuel in roughly 4 min, EVs require ~30 min at a fast charging station and up to several (>10) h for charging from a 110 or 220 V outlet, dependent on battery size (Saxton, 2013). Relative to a comparable ICEV, an EV's high purchase price, limited driving range, and long charge period all have a negative impact on adoption rate.

In addition to factors relating to the EV, consumer characteristics also play a role in determining uptake. Studies have identified levels of education, income, and environmentalism to all be positively correlated to likelihood to purchase an EV (Hidrué et al., 2011) or HEV (Gallagher and Muehlegger, 2011). However, these factors, specifically environmentalism, are often less important to consumers than vehicle cost and performance attributes such as those identified in the paragraph above (Lane and Potter, 2007; Egbue and Long, 2012).

³¹ 136 km.

A third set of elements, which the literature has found to influence adoption rates and is external to both the vehicle and consumer, is categorized as context factors in our research. In several studies, fuel (gasoline or diesel) prices have been identified as one of the most powerful predictors of HEV adoption (Diamond, 2009; Beresteanu and Li, 2011; Gallagher and Muehlegger, 2011), and have also been influential in agent-based models forecasting EV diffusion (Eppstein et al., 2011; Shafiei et al., 2012). Related to fuel prices, although less commonly incorporated in analyses, are electricity costs. Those two factors combine to determine a majority of EV operating expenses which in turn have an impact on adoption rates (Zubaryeva et al., 2012; Dijk et al., 2013). Other studies have identified availability of charging stations as an important determinant in consumer acceptance of alternative fuel vehicles e.g., EVs (Yeh, 2007; Struben and Sterman, 2008; Egbue and Long, 2012; Tran et al., 2013). A country's level of urban density could facilitate greater EV adoption as shorter average travel distances might allow for wider use of the vehicles' limited driving range (IEA, 2011). Finally, there are several factors specific to EVs that could influence adoption rates including vehicle diversity i.e., the number of models that consumers can buy (Van den Bergh et al., 2006), local involvement i.e., the presence of a local manufacturing plant (IEA, 2013), and public visibility i.e., the number of years EVs have been available for purchase (Eppstein et al., 2011).

5.4. Method

This section describes how EV adoption rates across a series of countries were analyzed using a set of socio-economic variables. Section 5.4.1 describes the data that were collected. Section 5.4.2 outlines a more detailed description of how financial incentives were operationalized. Section 5.4.3 provides the final model specification.

5.4.1. Data collection

We collected and analyzed data from 30 countries for 2012. The year 2012 was selected as the study date because important information such as charging infrastructure and EV adoption rates were unavailable in earlier years. Our statistical analysis used data from the following countries: Australia; Austria; Belgium; Canada; China; Croatia; the Czech Republic; Denmark; Estonia; Finland; France; Greece; Germany; Iceland; Ireland; Israel; Italy; Japan; the Netherlands; New Zealand; Norway; Poland; Portugal; Slovenia; Spain; Sweden; Switzerland; Turkey; the United Kingdom, and the United States. We selected these countries because of the availability of data, specifically EV adoption and charging infrastructure figures. In our study, we defined electric vehicles as including both pure battery electric vehicles, e.g., Nissan LEAF, as well as plug-in hybrid electric vehicles, e.g., Chevy Volt. As this definition of EVs was based around vehicles with a plug, other HEV models such as the Toyota Prius were not included in our analysis.

Based on the factors identified in Section 5.3, we collected data for the following variables for each country in our study: EV market share, financial incentives, urban density, education level, an environmentalism indicator, fuel price, EV price, presence of production facilities, per capita vehicles, model availability, introduction date, charging infrastructure,³² and electricity price. EV adoption was operationalized as national market shares of electric vehicles. Variable descriptions and their sources are provided in Table 5-1. Notable absences include driving range and charging time. Those variables were not added to our model because generally the same electric vehicles were available for purchase in the countries in

³² Charging stations were identified such that there could be multiple stations at a location, and multiple charging points (plugs) per station.

our sample. Thus, there is no fundamental difference in the driving range of a Nissan LEAF in China or a Nissan LEAF in Germany.³³

³³ Differences in temperature would affect driving range. With that in mind, the same vehicle in different countries might have slightly different performance characteristics depending on weather conditions. However, the precise effects of temperature on EV driving radii are still being determined. For that reason driving range as influenced by temperature was not included in our model, but could still contribute to differences in adoption between countries such as Spain and Sweden.

Table 5-1: Description of variables and sources

Variable	Data	Source
MarShr	National market share of electric vehicles as a percentage of all car sales	National automotive statistics websites
Incentive	Financial incentives that countries provided for the purchase and/or use of an electric vehicle	ACEA, 2012a; ACEA, 2012b; national government agencies
ChgInf	The number of charging stations ³⁴ in a country corrected for population (the number of charging stations per 100,000 residents)	Chargemap, 2013; lemnet.org, 2013; ASBE, 2013; Gronbil, 2013; national charging maps ³⁵
Env ³⁶	Index that ranks environmental regulation and performance by country and is intended to capture national differences in environmentalism	Yale, 2013
Fuel	The weighted average of national gasoline and diesel fuel prices. Averages were weighted based on the amount of gasoline or diesel fuel used in specific countries ³⁷	IEA, 2012a; Reuters, 2012; World Bank, 2012a; World Bank, 2012b
HQ	Dummy variable identifying whether a country had either an EV producer's global headquarters or production facilities	Auto manufacturer websites
Income	National income per capita as measured in purchasing power parity	World Bank, 2013a
PerCapVehicles	The number of vehicles per capita in a country	World bank, 2013a
Education	The percentage of workforce with at least a tertiary education level	World Bank, 2013b
Elec ³⁸	2011 household electricity prices per kWh	Eurostat, 2013; IEA, 2012a
Availability	Number of EV models that were purchased in 2012	Automotive statistics websites
Intro	Year (since 2008) that EVs were first sold in a given country	Marklines, 2013
EV_Price	The price of purchasing a Mitsubishi MiEV in a given country ³⁹	National Mitsubishi websites
UrbanDensity	Cumulative population per square mile in urban areas above 500,000 residents	Demographia, 2013

³⁴ A charging station with multiple outlets would be counted as one in these figures.

³⁵ For many countries, national charging maps were found to provide more comprehensive data than international websites such as www.chargemap.com.

³⁶ There is no concern of reverse causality between EV adoption rate and the EPI because the low numbers of electric vehicles being driven in countries would have a negligible impact on the indicators which make up the EPI.

³⁷ For example, if a country used 30% gasoline and 70% diesel, then their fuel price would reflect a greater weight placed on cost for diesel.

³⁸ Due to data availability issues, Iceland electricity prices were from 2012.

³⁹ In countries where MiEVs were not available, other EVs were used for a comparison e.g., the BYD F3DM in China.

5.4.2. Financial incentives

To encourage EV adoption, countries have used financial incentives from both technology specific policies, such as subsidies to EV consumers, and technology neutral policies, such as emissions-based vehicle taxes. These were applied either at the time of a vehicle's registration or on its annual circulation fee (license fees in the US). In some cases, countries lowered automobile taxes for EVs, and in others they provided subsidies apart from normal registration and circulation fees, thus presenting a very diverse financial incentive landscape. This section of the study describes how such a heterogeneous environment for subsidies was operationalized to allow for analysis across countries.

In order to compare financial incentives that used different emissions and monetary units, policies were standardized relative to CO₂ emissions and 2012 US dollars. To convert fuel use to CO₂ emissions, we used the following formula: 1 L/100 km = 23.2 g CO₂/km (UNEP, 2012). We converted currencies to US dollars using the averaged quarterly exchange rates from 2012. In some situations, it was necessary to use a vehicle's performance characteristics, e.g., CO₂ emissions⁴⁰ in order to calculate the financial incentives of a particular policy. An example would be an annual circulation fee in which the amount paid was dependent on a vehicle's CO₂ emissions levels. However, this does not give an indication of the savings relative to the purchase of an ICE vehicle (there is no basis for comparison). In order to calculate the value of such financial incentive policies, we used information from an ICEV and EV (a 2012 Volkswagen Golf and Nissan Leaf respectively). Table 5-2 provides a description of the basic characteristics of these vehicles.

Table 5-2: ICE vehicle and electric vehicle used for policy valuation

	ICE vehicle	Electric vehicle
Cost	\$25,000	\$35,000
Tailpipe emissions	140 CO ₂ g/km	0 g/km
Fuel efficiency ⁴¹	19 km/l	45 km/l ⁴²
Weight	1550 kg	1950 kg
Engine/battery pack	2.0 l 77 kW	20 kWh Li-ion

Some policies, such as registration taxes, were applied on a one-time basis. For other policies that required annual payments e.g., circulation fees, we sought to provide a more realistic notion of their monetary value. We did this by using a 3 year payback period and consumer discount rate of 30% (based on the work of Greene et al., 2005; Yeh, 2007). For example, a one-time registration subsidy of \$1000 maintains that value, but an annual circulation subsidy of \$50 provided a financial incentive of \$90.81 in our analysis.

For the countries studied in our sample, financial incentives did not change considerably in 2011 and 2012. In absolute terms during those 2 years, Portugal saw a \$5500 decrease in financial incentives offered to EV adopters while Finland saw a \$4600 increase. Otherwise, national financial incentive levels have remained constant over that time period.

⁴⁰ For the policies analyzed in our study, CO₂ emissions were calculated from a vehicle's tailpipe, based on standard driving cycles e.g., NEDC and FTP-75.

⁴¹ Based off the US FTP-75 driving cycle.

⁴² This is a liters per kilometer equivalent figure, and is common for estimating fuel economy for EVs.

5.4.3. OLS regression

The variables from Table 5-1 were incorporated into an ordinary least squares (OLS) regression with a logit transformation of the dependent variable to normalize distributions of EV market share. This transformation is appropriate when data are skewed, or bounded such as with a proportion (Lesaffre et al., 2007). A histogram of the EV market share was skewed to the right, and the variable was a proportion. After the logit transformation, a second histogram showed EV market share to be normally distributed, validating this approach. The final model specification is given as

$$\begin{aligned} \log_MarShr_i = & \alpha + \beta_1 Incentive_i + \beta_2 UrbanDensity_i + \beta_3 Education_i + \beta_4 Env_i \\ & + \beta_5 Fuel_i + \beta_6 ChgInf_i + \beta_7 Elec + \beta_8 PerCapVehicles + \beta_9 EV_Price \\ & + \beta_{10} Availability + \beta_{11} Introduction + \beta_{12} HQ + \varepsilon_i \end{aligned}$$

where the subscript i denotes the country, and ε is an error term.

5.5. Results and discussion

This section includes a correlation matrix of variables used in the model, a descriptive analysis of EV-specific factors, and results from the statistical model identified above. Stress tests of the model were employed to determine its general robustness and the relative impact of specific variables. Finally, we discuss implications that arise from the results, which provide a notion of how different policy measures such as fuel taxes, consumer subsidies, and installing charging stations could influence EV adoption.

5.5.1. Correlation analysis of model variables

Looking at relationships between individual variables can help to highlight dynamics that are not evident in linear regression models. Appendix D provides a Pearson's correlation coefficient and statistical significance between the variables used in the base model specification. One of the patterns that appears when analyzing this matrix is that many of the EV-specific variables are strongly correlated (price, year of introduction, availability, market share, financial incentives, and charging infrastructure), indicating that industrial dynamics can become interwoven during the early commercialization of a radical innovation. Another observation is that the EV price variable has a negative correlation to a country's market share. Mitsubishi MiEVs were most expensive in countries where adoption rates were low e.g., Turkey, China, and New Zealand, and they were cheaper in the US, Norway, and Japan, countries with relatively high EV market shares. Sometimes this difference was dramatic as with Australia (\$53,126) and Switzerland (\$26,925). And while it is difficult to draw any conclusive results from such correlations, they do provide a good basis for further analysis.

An additional correlation that was not included in Appendix D was between charging infrastructure and the type of EV (plug-in hybrid or purely battery electric). Potentially, a country with a higher proportion of plug-in hybrid-electric vehicles (PHEVs) would have less dependence on charging stations, which could weaken the relationship between a country's EV adoption and its charging infrastructure. However, preliminary model estimations identify that percent of PHEVs did not have a statistically significant relationship to either charging infrastructure or EV market share. This suggests that the proportion of a country's EVs with an internal combustion engine does not significantly relate to its charging infrastructure or adoption rate.

5.5.2. Descriptive analysis of EV-specific variables

In addition to socio-demographic factors such as income and education level, our model also incorporated several EV-specific variables including financial incentives, charging infrastructure, model availability, and presence of a local manufacturing facility. The descriptive analysis of these variables provided below identifies how significant correlations found in Appendix D can actually involve a great deal of heterogeneity and diversity, indicating the existence of other influential factors.

Financial incentives

Financial incentives and EV adoption in Figure 5-1 display a positive and significant relationship (P-value of .01). Even so, there is substantial variation among the data points. In addition, there appears to be two groups of countries. The first is constituted by approximately the bottom half of our study sample (14 countries) as represented by nations with financial incentives less than \$2000. They exhibited lower EV market shares with the exceptions of Sweden (0.30%) and Switzerland (0.23%), and to a lesser extent Germany (0.12%), and Canada (0.13%). Consequently, 10 countries showed little EV activity as measured by either financial incentives or EV adoption.

The other group in Figure 5-1 is distinguished by the countries with higher levels of financial incentives and greater variation in their EV market shares. Some countries such as Norway and Estonia matched high financial incentives with increased EV adoption. However, this relationship was not uniform as other countries, including Denmark and Belgium, offered high financial incentives but had relatively low levels of adoption. Figure 5-1 suggests that there are factors other than financial incentives that drive EV adoption.

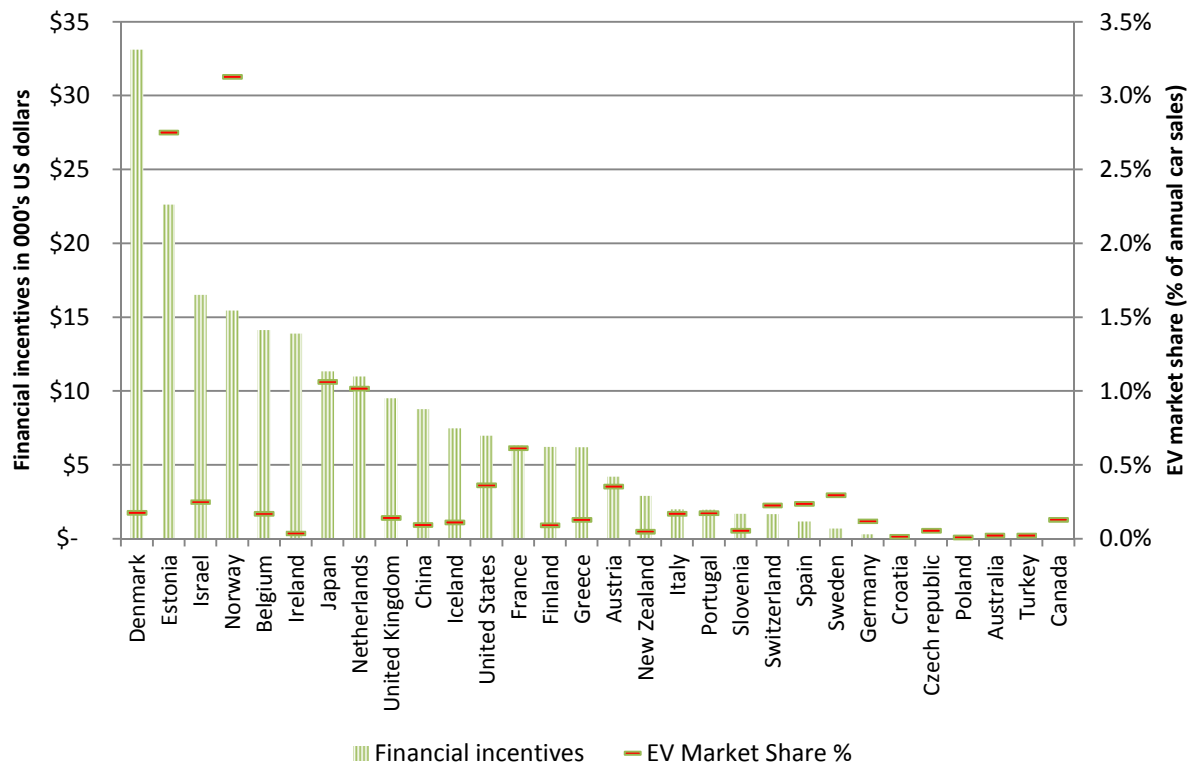


Figure 5-1: Financial incentives by country and corresponding EV market share for 2012

In addition to variables captured by the model, there are likely to be country-specific factors that influenced national EV market shares. For instance, consumers in Estonia adopted 55 EVs in 2011 (Mnt.ee, 2013), but the federal government decided to purchase approximately 500 MiEVs in 2012 (Estonia, 2011). That single act largely explains why it had such a high market share in 2012. Conversely, Norway installed extensive charging infrastructure in 2009, and has experienced a more gradual increase in EV adoption rates since 2010, predominantly through household consumers (SAGPA, 2012). An additional factor which is not captured by the financial incentive variable is the subsidy's recipient. Through their purchase of a majority of EVs through 2012, fleet managers were identified as being very important early adopters (IEA, 2013). However Belgium's financial incentives were directed specifically toward households, so they may have largely missed engaging the fleet market, hurting the country's adoption figures. These country specific factors provide insight into factors not included in the model that had the potential to greatly influence national EV adoption levels.

As identified in Section 5.4, countries employed several different types of financial incentives based on the vehicle's tonnage, company car status, emissions, and powertrain, which can be broadly categorized as either registration or circulation subsidies. Figure 5-2 identifies how countries approached financial incentives according those policy categories.

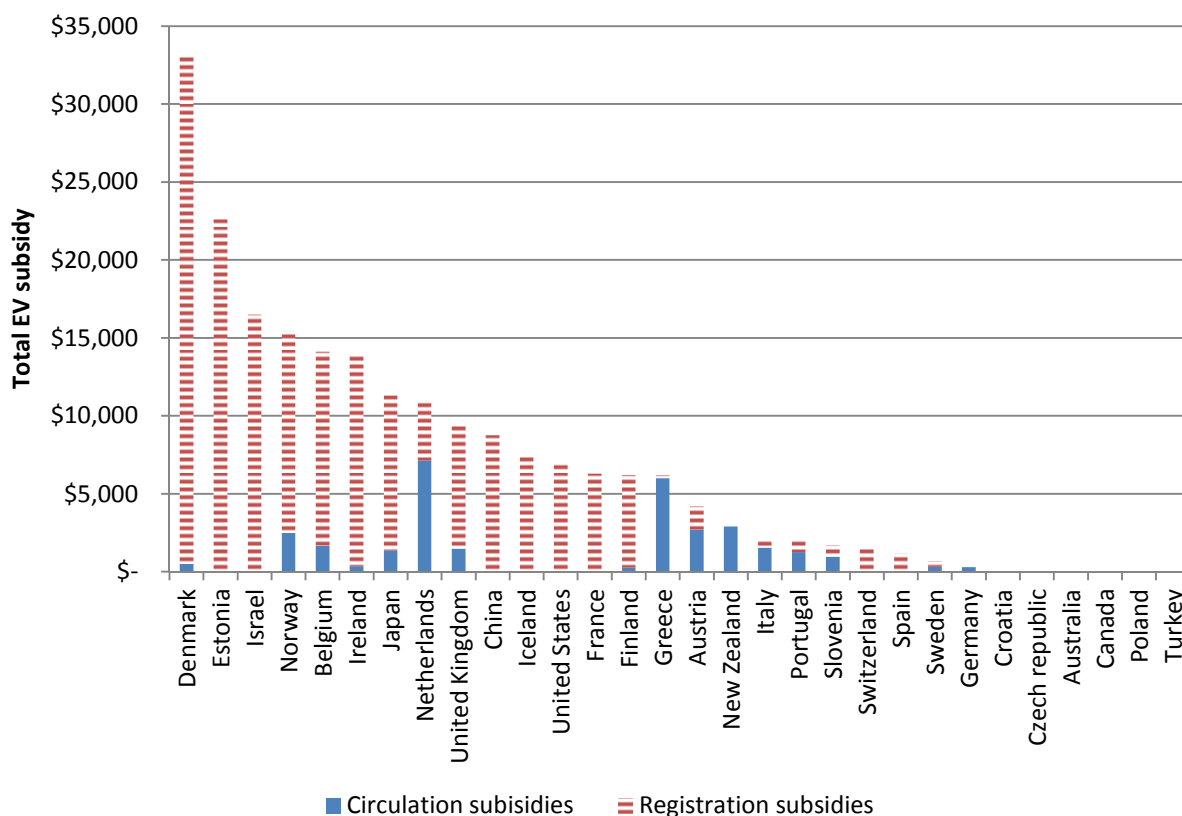


Figure 5-2: Breakdown of financial subsidies types offered by countries in 2012

Figure 5-2 notes that most available EV financial incentives (78%) came in the form of registration as opposed to circulation subsidies. The difference between the two is that registration funds were offered the year that the EV was purchased while those based on a vehicle's annual circulation provided benefits over a multiple year time span. Perhaps one reason why registration subsidies were the dominant form of financial incentives is due to consumer high discount rates for circulation subsidies, effectively lowering their perceived value. A correlation test between EV market share and registration/circulation subsidies did

not return a significant value suggesting that it was the total financial incentive value and not the specific policy type that was relevant for adoption rates.

Charging infrastructure

Figure 5-3 exhibits a positive and significant relationship (P-value of .000) between charging stations (adjusted for population) and EV adoption rates. Despite an overall positive correlation, there were examples of wide discrepancies in the data as evidenced by Estonia and Israel. Both countries had similar proportions of charging stations, but Estonia had an EV adoption level 11 times higher than that of Israel. There also appears to be seven countries with very low levels of both charging stations and EV adoption.

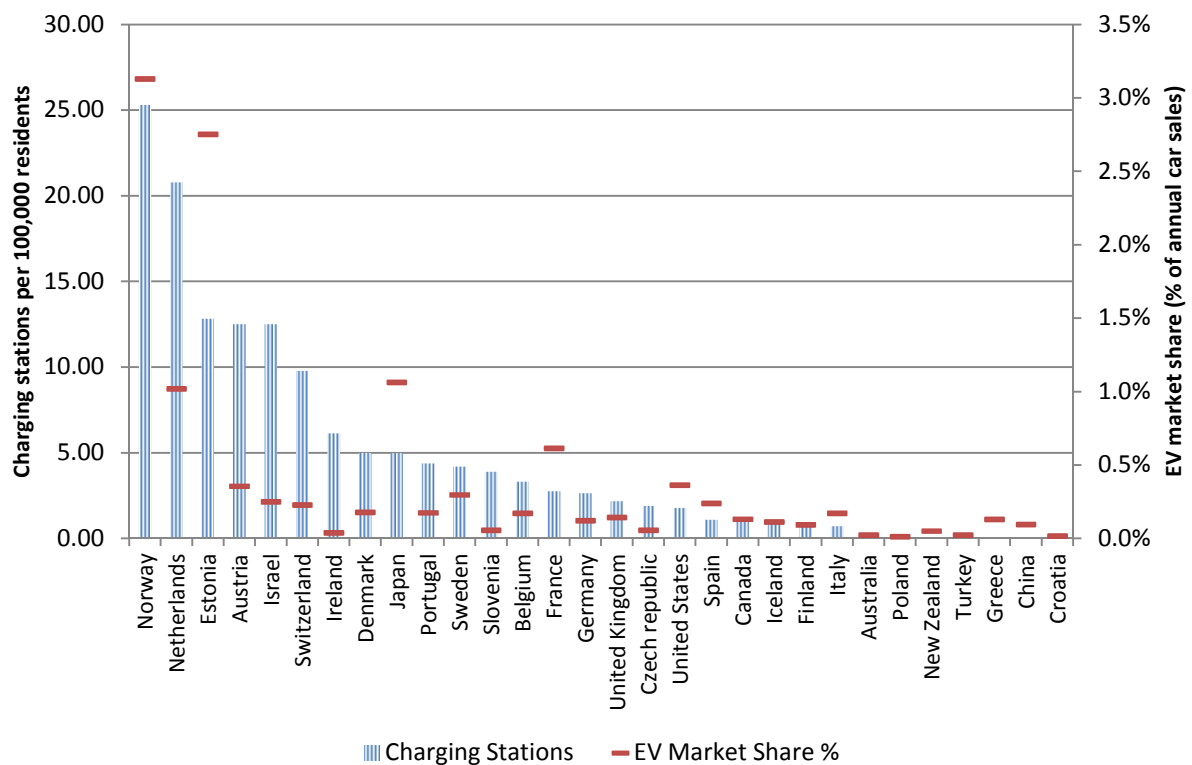


Figure 5-3: 2012 national charging infrastructure and EV market share by country

Not as much information is available about national charging infrastructure as financial incentives, perhaps because in many countries they are largely installed by local municipalities (Bakker and Trip, 2013). Among the countries in our sample, there have been several different approaches to building charging infrastructure from federal mandate (Estonia) to auto manufacturer led (Japan) to local government initiative (Belgium) to public-private partnerships (Norway) (Estonia, 2011; SAGPA, 2012; ASBE, 2013; Nobil, 2012). This variety in approach to charging infrastructure development likely relates to other factors that influence EV adoption e.g., local involvement.

Analyzing Figures 5-1 and 5-3, five (out of the 30) countries showed very little activity during the introductory phase of EVs, as measured by financial incentives, adoption, or charging infrastructure installation. Thus, countries in our study could be divided into two groups with divergent attitudes toward EV adoption as reflected by government policy and consumer purchase behavior. One set of countries seemed to be actively engaged in the EV introductory market while the other appeared to show very little interest. However, the

discrepancy between the two groups will likely have little effect on the overall success or failure of EVs as the countries invested in their adoption represent a substantial majority of global GDP based on national purchasing power parity (World Bank, 2013c).

Number of models available and local EV production

As identified in the correlation matrix, many of the EV-specific variables displayed strong correlations. In order to better understand how these factors interact, Figure 5-4 looks at three such variables: the number of models available for purchase; whether a country produced EVs locally (bolded columns); and adoption rates.

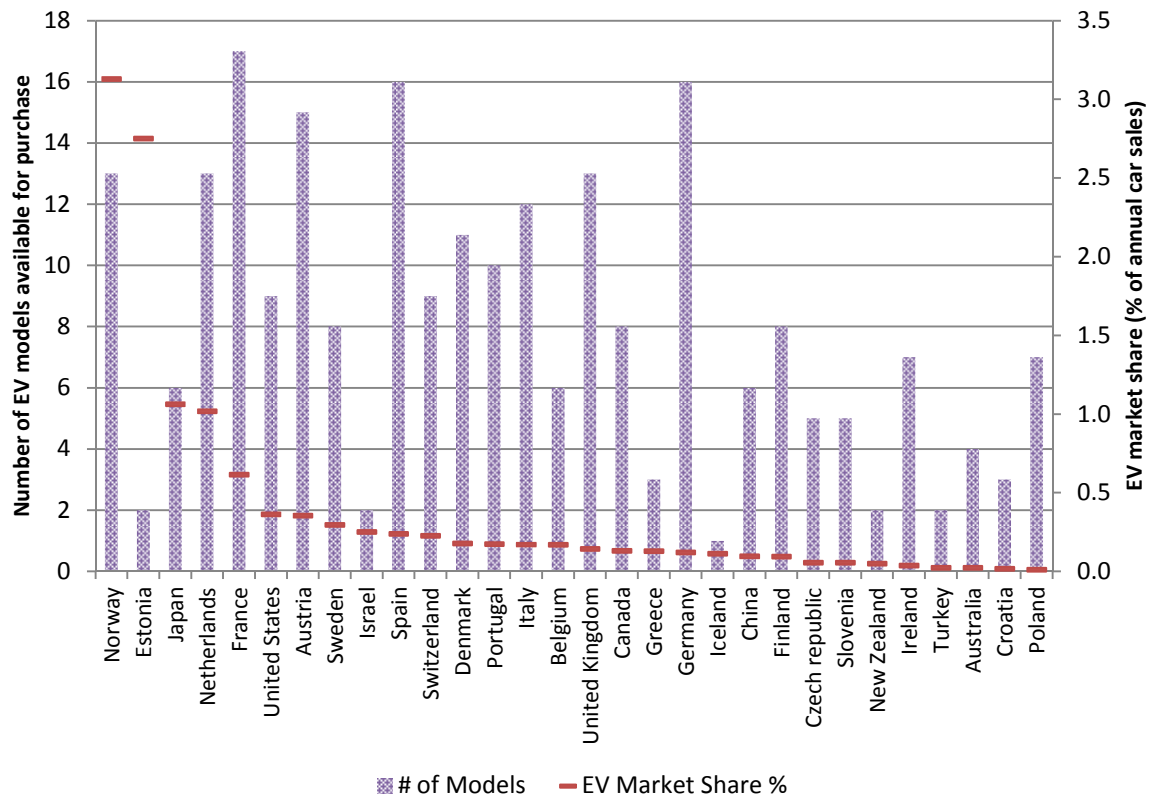


Figure 5-4: Number of EV models available for purchase, production facilities, and national market shares in 2012

In total, 45 different types of EVs were purchased in 2012 although a small number of models such as the Nissan Leaf, Chevy Volt/Opel Ampera, and Toyota Plug-in Prius accounted for the lion's share (62%) of those sales. The Mitsubishi MiEV was the most widely available, being adopted in 26 of the countries in our sample. There was a positive correlation between a country's EV adoption rate and the number of models that were available for purchase. In many instances, manufacturers sold a limited number of several different EV models in their native country e.g., Ford in the US and Mercedes in Germany. In those instances, manufacturers were likely experimenting with a limited production of specific EV models before expanding their sales efforts.

Countries where native manufacturers heavily invested in EVs e.g., Japan, France, and the US, had some of the highest EV market shares. Other countries with EV production facilities but low adoption rates including Germany and Italy did not have EVs made by native manufacturers broadly available. This suggests a strong relationship between consumer

adoption of EVs and their being manufactured by native firms. Several of the larger countries were much more prone to adopt native models, specifically China and Japan where only EVs from native manufacturers were purchased. Of those two countries, China stands out because very few EVs made by Chinese auto makers were sold outside the country. Many manufacturers e.g., Ford, Audi and Mia Electric, were nation-specific with sales only or primarily occurring in the country where their production facilities were located. The relationship between the variables in Figure 5-4 suggests a complex relationship between consumers, manufacturers, and national attitude regarding EVs.

5.5.3. OLS model results and implications

Table 5-3 shows regression results from the 30 countries in our study for 2012. We regressed the log of EV market share on financial incentives, urban density, education level, an environmentalism indicator, fuel price, EV price, the presence of production facilities, per capita vehicles, model availability, introduction date, charging infrastructure, and electricity price. We used graphical and numerical analyses to ensure that the data met expectations of linearity, normality, and homoskedasticity. We used ANOVA tests and histograms to test for linearity, Shapiro–Wilk tests for normality, and visual analysis of scatter plots for heteroskedasticity.

Table 5-3: Regression results for 2012 electric vehicle adoption

	Unstandardized B (Std. err.)	Standardized Beta
(Constant)	-5.703 (2.858)	
Incentive	0.006 (0.003)*	0.357
Charging infrastructure	0.131 (0.039)**	0.599
Environment	0.020 (0.037)	0.106
Fuel	-0.141 (0.827)	-0.031
HQ	0.926 (0.492)+	0.312
Income	-0.046 (0.036)	-0.336
Per capita vehicles	0.003 (0.002)	0.319
Education	0.030 (0.003)	0.190
Electricity	-0.221 (0.282)	-0.115
Availability	0.049 (0.056)	0.178
EV introduction	0.122 (0.232)	0.106
EV Price	0.008 (0.029)	0.046
Urban density	0.018 (0.077)	0.056
N	30	
R ²	0.792	
Adjusted R ²	0.623	

** P<.01

* P<.05

+ P<.1

The model's adjusted R² was 0.628 which means that almost 2/3 of the variation in national EV market shares was explained by the tested variables. The coefficients for financial incentives and charging infrastructure were positive and statistically significant with P-values of 0.039 and 0.004 respectively. Of those two variables, charging infrastructure had higher

Beta values (both standardized and unstandardized), indicating that it was stronger at estimating adoption levels. Thus, adding a charging station (per 100,000 residents) had a greater impact on predicting EV market share than did increasing financial incentives by \$1000. The presence of a local EV manufacturing facility was also a significant variable, although to a lesser extent with a P-value of 0.079.

From the information in Table 5-3, it is possible to extrapolate the relationship of both financial incentives and charging infrastructure to EV market share. Holding all other factors constant, each \$1000 increase in financial incentives would cause a country's EV market share to increase by 0.06%. For example, a country with an EV market share of 0.22% that increased its financial incentives to consumers by \$2000 would see its adoption rate go up to 0.34% (0.22% + 0.06% + 0.06%). For charging infrastructure, holding all other factors constant, each additional station per 100,000 residents that a country added would increase its EV market share by 0.12%. This suggests that each charging station (per 100,000 residents) could have twice the impact on a country's EV market share than \$1000 in consumer financial incentives, albeit with different bearings on a nation's budget.

However, as a note of caution, while our model did identify that financial incentives and charging infrastructure were positively correlated to national EV adoption levels, there is no guarantee that these relationships hold for all countries, as evidenced in Figures 5-1 and 5-3. For example, in Figure 5-1 Belgium and Denmark had very high financial incentives, but relatively low rates of adoption. Conversely, Switzerland and Sweden exhibited the opposite dynamic with low consumer subsidies but high EV uptake levels. Figure 5-3 displayed the same sort of mixed relationship between charging infrastructure and EV market share. Thus, financial incentives and charging infrastructure should be seen as being likely but not certain to predict a country's EV adoption rate.

The empirical results provide a useful comparison with stated preference surveys. While charging infrastructure and financial incentives were (as expected) significant in predicting EV adoption, this was not the case with broader socio-demographic variables e.g., income, education, environmentalism, and urban density that the literature had anticipated to be influential (Lane and Potter, 2007; Gallagher and Muehlegger, 2011; Egbue and Long, 2012). In addition, despite its strong and positive correlation to HEV adoption in earlier studies (Diamond, 2009; Beresteanu and Li, 2011; Gallagher and Muehlegger, 2011), fuel price was not significant in predicting a country's EV market share. However, there are fundamental differences in those papers and our study that could help explain these conflicting results. Firstly, the HEV studies examined a single nation over several years whereas our study looked at several countries for a single year. Secondly, fuel prices in those earlier studies exhibited much greater variation than was found in our data. Conversely, it could be that differences such as the complexity of total ownership cost calculation and the role of charging infrastructure result in fuel prices not having the same impact on EV purchases that they do with HEVs. More research is necessary to identify the relationship between fuel price and EV adoption, specifically studies that span multiple years and look at a single country.

Sensitivity tests

In addition to econometric results found in Table 5-3, we also performed several estimations to test the sensitivity of different variables (specifically financial incentives and charging infrastructure) and the base model's overall robustness. These are described below in Tables 5-4 and 5-5 and are referred to as Models 1–5 respectively. The individual variable(s)

explored through sensitivity analysis is identified below the Model's number e.g., charging infrastructure in Model 1.

Table 5-4: Model sensitivity analyses 1 and 2

	(1) ChgInf	(2) Incentive
(Constant)	-5.368 (2.893)	-5.380 (2.791)
Financial incentive	0.006 (0.003)*	0.066 (0.029)*
Charging infrastructure	0.164 (0.05)**	0.122 (0.040)**
Environment	0.019 (0.038)+	0.021 (0.037)
Fuel	-0.182 (0.841)	-0.137 (0.819)
HQ	0.847 (0.492)	1.007 (0.490)+
Income	-0.047 (0.037)	-0.039 (0.036)
Per capita vehicles	0.003 (0.002)	0.002 (0.002)
Education	0.025 (0.03)	0.027 (0.030)
Electricity	-0.236 (0.285)	-0.216 (0.279)
Availability	0.053 (0.057)	0.045 (0.055)
EV Introduction	0.145 (0.233)	0.077 (0.234)
EV price	0.009 (0.029)	0.006 (0.028)
Urban density	0.012 (0.078)	0.009 (0.075)
N	30	30
R ²	0.787	0.795
Adjusted R ²	0.613	0.628

** P<.01

* P<.05

+ P<.1

In Model 1, normalizing charging infrastructure for urban density did not drastically affect results with the variables financial incentives, production facilities, and charging infrastructure remaining significant while the adjusted R² (0.613) was also similar to that of the base estimation. As such, the base model remains robust to this sensitivity test. Model 2 explored the sensitivity of EV adoption to financial incentives with different discount rates and payback periods. While the US Energy Information National Energy Modeling System uses a 3 year payback period and discount rate of 30%, other studies have found that consumers, specifically businesses and government agencies, may more accurately calculate the total lifetime costs of an innovation (Nesbitt and Sperling, 1998; Menanteau and Lefebvre, 2000). As such, we ran a sensitivity test for a lower discount rate (1.25%) and longer payback period (8 years, which is the warranty period for a Nissan Leaf or Chevy Volt). This approach resulted in \$25,000 more in available financial incentives from \$180,000 in the base model. This sensitivity test did not substantially change the significant variables (financial incentives, charging infrastructure, and EV manufacturer location) or the models adjusted R², (0.628) suggesting that differences in discount value and payback period have a relatively weak influence on national EV adoption rates, although that could be due to the small number of multi-year consumer subsidies i.e., those that address circulation taxes.

Table 5-5: Model sensitivity analyses 3–5

	(3) Incentive	(4) ChgInf	(5) Incentive & ChgInf
(Constant)	-3.692 (3.021)	-5.519 (3.629)	-2.756 (3.842)
Financial incentive		0.008 (0.004)**	
Charging infrastructure	.149 (.042)**		
Environment	.000 (.040)	0.020 (0.048)	-.007 (.052)
Fuel	.337 (.889)	0.548 (1.018)	1.321 (1.078)
HQ	.908 (.547)	0.418 (0.595)	.301 (.663)
Income	-.056 (.040)	-0.013 (0.044)	-.021 (.049)
Per capita vehicles	.002 (.002)	0.069 (0.002)	-.002 (.002)
Education	.047 (.032)	0.037 (0.038)	.062 (.041)
Electricity	-.044 (.302)	-0.458 (0.347)	-.261 (.377)
Availability	.024 (.061)	0.092 (0.069)	.065 (.077)
EV introduction	.222 (.253)	0.349 (0.282)	.527 (.304)
EV price	-.007 (.031)	-0.005 (0.036)	-.028 (.039)
Urban density	-.043 (.080)	-0.017 (0.097)	-.105 (.100)
N	30	30	30
R ²	0.726	0.643	0.527
Adjusted R ²	0.533	0.391	0.238

** P<.01

* P<.05

+ P<.1

Sensitivity analyses 3–5 show how the model's explanatory power changed with the removal of financial incentives and charging infrastructure variables. Removing the financial incentives variable in Model 3 resulted in the adjusted R² decreasing from 0.623 in the base analysis to 0.533. Taking out charging infrastructure in Model 4 caused a more drastic reduction in adjusted R² to 0.391. Removal of both factors in Model 5 caused the model to lose most of its explanatory power; it had no significant variables and an adjusted R² of 0.238. From these sensitivity tests it is possible to conclude that in our model, charging infrastructure was considerably stronger than financial incentives in explaining EV adoption rates.

There were several limitations in our models which had the potential to produce misleading results. During the introduction of new technologies, there are often discrepancies in supply among locales. Differences in EV availability by locality may have contributed to variation in national adoption numbers. In addition, our study analyzed financial incentives from national governments. There are undoubtedly monetary benefits, such as free parking or toll exemptions provided by regions and cities that were not included in this study and were likely to have been influential. The small number of observations per year is also cause for caution when interpreting the results. Furthermore, by only studying 1 year, the data does not allow for analysis of the relationship between important variables e.g., financial incentives and charging infrastructure.

5.6. Conclusions

The purpose of this research was to explore the relationship between financial incentives and other socio-economic factors to electric vehicle adoption across several countries. We found that financial incentives, the number of charging stations (corrected for population), and the presence of a local EV manufacturing facility were positive and significant in predicting EV adoption rates for the countries in our study. Of those variables, charging infrastructure was the best predictor of a country's EV market share. However, descriptive analyses indicated how country-specific factors such as government procurement plans or the target recipient of subsidies could dramatically affect a nation's adoption rate. On the whole this analysis provides tentative endorsement of financial incentives and charging infrastructure as a way to encourage EV adoption.

A second conclusion is that EV-specific factors were discovered to be significant while broader socio-demographic variables such as income, education level, and environmentalism were not good predictors of adoption levels. This could be because national EV markets were so small relative to overall automobile sales. Thus, while many EV consumers may have high levels of education and be passionate about the environment, within the perspective of a country such individuals still represent a tiny portion of the overall population. Therefore, socio-demographic variables may not provide a good indicator of adoption levels when comparing countries. If EVs emerge from a niche market, then socio-demographic data might be more accurately used to predict adoption levels at the national scale. Until then, EV-specific factors such as amount of charging infrastructure, level of consumer financial incentives, and number of locations that sell the automobiles are likely to be more correct for estimating a country's market share.

5.6.1. Policy implications

Based on our results, a sensible policy approach for addressing EV market failures arising from pollution abatement and knowledge spillover would be for governments to provide consumer subsidies and/or increase their number of charging stations. Due to the importance of consumer adoption during the commercial introduction of a radical innovation (Nemet and Baker, 2009), such supportive measures could make a wide difference in the level of EV diffusion in the coming decades. As the charging station variable was the strongest predictor of EV adoption based on Beta values stress tests, their installation may be more effective than financial incentives. However, since these two factors are likely to be complimentary, supporting both measures could be expected to lead to higher market shares than focusing on either financial incentives or charging infrastructure alone.

However, this study also provides three notes of caution to countries that expect that they can achieve high EV adoption rates by increasing their levels of financial incentives or charging infrastructure. Firstly, the descriptive analysis identified several countries that displayed a relatively weak relationship between the two factors and EV market share. Secondly, it is possible that financial incentives or charging infrastructure mask other dynamics which are significant in driving EV adoption. Consequently, building policy only around those two factors may not support important underlying elements. Thirdly, due to the constantly evolving environment during the emergence of a radical innovation, industrial dynamics may change from year to year. Therefore, while this study does show that financial incentives and charging infrastructure are positively correlated to national EV market shares, it is definitely not evidence of a causal relationship and should be treated with prudence.

While national governments have been primarily responsible for consumer financial incentives, installing charging points has largely been left to local public bodies such as cities (IEA, 2013). However, the IEA (2013) found that “infrastructure spending has been relatively sparse” (pp. 16), which suggests that local and national levels of government should strengthen coordination in order to better encourage EV adoption, supporting earlier research by Bakker and Trip (2013).

Now that we have identified policies that could be effective in encouraging EV adoption, a next question is whether they are actually efficient in a societal and economical sense. To answer this question, an elaborate ex-ante Cost Effectiveness Analysis (CEA) or Cost Benefit Analysis (CBA) would be needed. However, given the dynamic nature of radical innovations, one should be careful when applying these methods to the EV case. That is to say, EVs may not significantly reduce GHG emissions in the short term, but they have the potential to cause dramatic decarbonization post 2020 (IEA, 2012c), assuming a dramatic increase of the share of renewables in the electricity mix. In that respect, financial incentives today may be important for stimulating broader EV adoption in the future, and consequently may provide benefits outside those typically included in a status quo based CBA. Such additional benefits may be reason to implement these policies even if the results from a traditional CBA were not very favorable.

Furthermore, it is difficult to compare the costs of financial incentives for EVs with at least some competing policy options to reduce CO₂ emissions. Financial incentives to increase the sales of EVs on a temporary basis may be needed in the early stages of EVs because they cannot compete yet with internal combustion engine vehicles. If, in a few decades, EVs would become a success, financial incentive policies could prove to have contributed to this success. In other words, there may be a snowball effect of current financial incentives which are fundamentally difficult to grasp in a conventional CEA or CBA. We therefore suggest that these analyses can be used to support decision making, but that their outcomes should be treated with caution and that decision makers should always take a long term perspective when interpreting these.

5.6.2. Suggestions for future research

This study looked at a country's total charging infrastructure, not taking into account how a heterogeneous distribution of charging stations (many in one city, few elsewhere) might influence EV adoption. Specifically because of the important role played by local municipalities in installing charging infrastructure, their allocation could have an important affect on a country's EV adoption rate (Bakker and Trip, 2013). Therefore, we suggest that future research focus on the relationship between the distribution of charging infrastructure within a country and its EV adoption rate.

In addition, our model found charging infrastructure and financial incentives to be powerful predictors of EV adoption rates for the countries in our sample. However, it is possible that the variables concealed other important factors. Therefore, further analysis is necessary to unpack the importance of charging infrastructure and financial incentives to determine whether they are on their own good predictors of EV adoption, or if there are other elements that also need to be present but were not included in our model. For instance, fuel price volatility may provide insight into EV adoption that is not captured through absolute fuel prices.

Acknowledgments

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6. Fleet manager adoption of electric vehicles

Sierzchula, W. (2014) Factors influencing fleet manager adoption of electric vehicles, in: *Transportation Research Part D: Transport and the Environment* 31, 126-134.

Abstract

Research has identified several reasons why fleet managers are good candidates to be electric vehicle (EV) early adopters such as their intense usage and high automobile purchase rates. This expectation is supported by a recent study which found that to 2013, governments and private companies were responsible for a majority of global EV purchases. Using content analysis of fleet manager interviews and pilot project reports, this study investigated 14 US and Dutch organizations that adopted EVs from 2010-2013 to determine which factors influenced their purchase decisions. In addition, it also analyzed the reasons why these same firms did or did not expand their EV fleets. Fleet managers identified testing new technologies as being the overarching driver of their initial adoption of EVs. Organizations also noted several influential but secondary factors including lowering their environmental impact, government grants, and improving the organization's public image. For organizations that decided to expand their EV fleets, the primary motivating rationales were firm-specific, including pursuing first-mover advantage, specialized operational capabilities, or a compelling business model.

6.1. Introduction

The IPCC (2007) noted that to avoid potentially catastrophic environmental, social, and economic consequences from climate change, there needs to be substantial decreases in greenhouse gas emissions (GHG), specifically in the energy production and transportation sectors. Electric vehicles (EVs) have been identified as one of the most promising technologies in the transportation sector to reduce GHG emissions in the post 2020 timeframe (IEA, 2013). However, there is a whole series of barriers that limits their emergence and wide-spread adoption including the development of new technologies, replacing support infrastructure, and auto manufacturer investment (Tran et al., 2013).

In addition, because EVs entail fairly dramatic operational and performance differences relative to the dominant internal combustion engine vehicle (ICEV) design, wide-spread adoption would also require adjustments in consumer understanding, heuristics, and automobility expectations (IEA, 2011). The requisite changes in consumer beliefs toward a radical innovation such as EVs helps to explain why establishing a customer base is one of the main obstacles hindering their early adoption (Christiansen, 1997). Through several factors including decreased battery costs and the installation of charging infrastructure, a customer base for EVs has emerged with 2012 global sales reaching approximately 113,000 units (IEA, 2013). A majority of these EVs were purchased by governments and firms (Frost and Sullivan, 2013), identifying the importance of organizations during the innovation's early adoption phase. For example, FedEx purchased 200 EVs (Scientific American, 2013), and the French government has been coordinating a plan to procure 50,000 of the automobiles for public and private organizations (IEA, 2013; Green.autoblog.com, 2010).

Researchers have identified several reasons why organizations are good candidates to be early EV adopters including their high vehicle purchase rates, intense usage, (frequently) centralized refueling stations, and limited number of decision makers (Nesbitt and Sperling, 1998; IEA, 2011; Bobit, 2012; Dijk et al., 2013). Fleet managers also have a better comprehension of lifetime vehicle costs than do private households (Lane and Potter, 2007; Sovacool and Hirsch, 2009). Consequently, organizations are more likely to adopt vehicles that have high purchase costs but offer the potential of lower total ownership costs through reduced operating expenses.

Although studies have acknowledged organizations to be major adopters during EV market introduction (Frost and Sullivan, 2013), research identifying factors that influence fleet manager purchase decisions was either conducted before the recent broad commercialization (Nesbitt and Sperling, 1998; Nesbitt and Sperling, 2001) or was not based on empirical data (IEA, 2013; Dijk et al., 2013). As such, the theory regarding fleet manager EV adoption should be updated now that the automobiles are available for sale and revealed consumer behavior (empirical data) can be analyzed. In that regard, this article centers around the following research question, *what were the important factors that influenced fleet managers' initial EV adoption?* An additional and related area for analysis is why organizations did or did not expand their EV fleets. Thus, a second research question is, *which factors determined whether or not organizations increased their EV fleets?* The purpose of this study is to develop testable hypotheses regarding the driving forces behind fleet manager EV adoption. It will also provide policy recommendations for achieving higher EV diffusion through encouragement of adoption by organizations.

6.2. Method

This study selected to use a qualitative case study method for three reasons. Firstly, the low level of EV adoption by organizations generally precluded a large-scale statistical analysis. Secondly, the method is particularly suited to building theory, which is the goal of this article (Eisenhardt, 1989). Thirdly, interviews allow for a more in-depth analysis of a case than is possible through quantitative methods (Yin, 2009).

In line with the paper's goal of building theory, it employed a theoretical sampling and inductive reasoning approach. As opposed to *statistical sampling* where the test group is designed to be representative of a population, cases in *theoretical sampling* are purposefully selected for their diversity. Inductive reasoning seeks to derive hypotheses based on the evidence given as opposed to deductive reasoning which examines the validity of preexisting theory. Consequently, the combination of theoretical sampling and inductive reasoning is particularly appropriate when the research goal is to develop new concepts instead of testing existing ones.

To examine the data the study used content analysis, which is a systematic and replicable method of investigating communication (Berelson, 1952; Weber, 1990). It involves developing textual categories according to specific rules and the subsequent codification of terms within the data. The study employed an emergent coding method (Krippendorff, 2004), where two researchers used a preliminary set of the data to independently identify factors that influenced fleet manager EV adoption e.g., 'low total ownership costs'. These factors were categorized into what is known in content analysis as textual categories. The researchers then reconciled any differences between their respective textual categories to create a single consolidated checklist.

When using this checklist, coders looked for not only the existence, but also the strength and sign of textual categories within individual interviews. Strength identified the importance of specific instances within textual categories, and following Carley (1993), was rated on a 1 to 3 scale with 1 being implied, 2 explicitly stated, and 3 emphasized. Sign was determined by whether the factor had a positive or negative influence on fleet manager decisions to adoption EVs. For quantitative analysis, the frequency, sign, and strength of different textual categories were calculated. As complementary qualitative analysis, specific instances within textual categories were used to identify patterns that may not have been evident in the quantitative examination because the factors were reduced to coded numbers. For example, 'new performance capabilities' is an overarching textual category which may mask important aspects such as the identity of those capabilities and how specifically they encouraged EV adoption.

Investigator triangulation was used throughout the research process to improve validity and minimize biases (Denzin, 1970). Researchers came to agreement regarding the initial textual categories. Similarly, both quantitative and qualitative analyses were verified through area experts coming to consensus regarding data results. Finally, Krippendorff's alpha was used to evaluate intercoder reliability. That particular measure was selected because it corrects for chance agreement between coders, allows for ordinal data, and does not require a minimum sample size (Krippendorff, 2004). It is assessed on a 0 to 1 scale, with a value of 1 indicating perfect agreement and 0.9 being a common threshold for data reliability (Neuendorf, 2002). Two researchers' coding of the existence, strength, and sign of textual categories within a

sample of the interviews⁴³ resulted in a Krippendorff alpha of .913, attesting to its reliability. Instances of disagreement were settled by a third coder with expertise in the research topic.

6.3. Data

Data for this study came from eleven 30-60 minute semi-structured interviews and three project reports (where interviews were not possible). Content analysis is particularly suited to this research setup because it allows for data to come from different types of sources e.g. interviews and project reports (Neuendorf, 2002). The sample size was appropriate because the study used theoretical as opposed to representative sampling (Eisenhardt and Graebner, 2007), an approach that has been used in similar research for photovoltaic cells (see Hoppmann et al., 2013). Each interview consisted of a set of eight standard questions with the flexibility for the interviewer to explore particular areas of interest as they arose. A fleet manager from each organization was interviewed, and these conversations were transcribed for analysis. In the three cases where written reports were used, they covered completed pilot projects, and addressed each of the interview's standard questions.

As the purpose of this article was specifically to build theory, it was important that the study sample included a diverse group of organizations as opposed to a large number of cases (Eisenhardt and Grabner, 2007). In order to assure sample diversity, the study used a broad assortment of organizations based on their public/private status, size, industry, and the number/type of EVs used. Researchers investigated six public and eight private organizations from the Netherlands and United States that adopted electric vehicles from 2010 to 2013, a timeframe which encompassed the recent mass commercialization of EVs (Sierzchula et al., 2012). Table 6-1 presents an overview of the different types and sizes of organizations included in the study sample. In line with Eurostat, a threshold of 50 employees was used to differentiate between small (x) and medium/large (X) organizations (Eurostat, 2005). While all of the public agencies in the sample had more than 50 employees, the private firms ranged in size from startups to multi-national corporations. Electric vehicles were defined as automobiles that charged their battery with a plug; this included full electric vehicles e.g., the Nissan Leaf and plug-in hybrid-electric vehicles⁴⁴ e.g., the Chevy Volt. Organizations held a wide assortment of electric automobiles including: low-speed EVs⁴⁵, larger maintenance and utility vehicles e.g., Ford Transit Connect, and passenger EVs e.g., Nissan Leaf, Peugeot iOn, and Toyota Plug-in Prius. In addition, there was also a considerable difference in the number of EVs that organizations had purchased, ranging from three to hundreds.

⁴³ It is common practice within content analysis for both textual category identification and coding to use at least 10% of the data (Lombard et al., 2004). For this study, that sample consisted of three interviews or 21% of the data.

⁴⁴ These vehicles combine a battery and electric motor with an internal combustion engine.

⁴⁵ These are small vehicles with a top speed of approximately 25 miles per hour.

Table 6-1: Overview of study sample

		Firm 1	Firm 2	Firm 3	Firm 4	Firm 5	Firm 6	Firm 7	Firm 8	Firm 9	Firm 10	Firm 11	Firm 12	Firm 13	Firm 14
Public organization	City	X	X												
	State			X	X	X									
	National						X								
Private organization	Taxi							x	X						
	Industrial									X	x	X			
	Carshare												X	x	
	Car rental														X

6.4. Results and discussion

The following section presents this study's results relative to the research questions that were identified in the introduction. Through a combination of qualitative and quantitative analysis, results are also discussed according to an organization's status (public or private), size (small or large), industry, and the number/type of EVs used. The sign of textual categories that influenced fleet manager EV adoption decisions is indicated in Tables 6-2, 6-4, and 6-5 by symbols '+' (positive effect) and '-' (negative effect). Category strength is identified with numerals 1-3; a score of 1 indicates implied meaning, 2 denotes that a category was explicitly stated, and 3 signifies that it was emphasized.

6.4.1. Initial EV adoption

Table 6-2 shows the factors (labeled as textual categories) which influenced fleet managers' initial decisions of whether or not to adopt an EV. These factors are analyzed below as they relate to broad as well as firm-specific dynamics.

Table 6-2: Factors that influenced fleet managers' initial adoption of electric vehicles

Textual categories	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5	Firm 6	Firm 7	Firm 8	Firm 9	Firm 10	Firm 11	Firm 12	Firm 13	Firm 14
Total ownership cost	-1	-1	-1	-2	-2	+3		-1		-1			-1	-1
Fixed routes				+1						+1				+1
Central refueling				+1			+2		+1					+1
First mover advantage								+3				+3	+3	+3
Lower env. impact		+2	+2	+2		+2	+1	+1	+2			+1	+1	+3
Govt. regulation				+3	+2									
Govt. grant	+2	+1	+1		+1		+1	+1			+1		+1	
Test new technologies		+3	+1	+3	+3	+3				+1	+1	+3	+3	+3
Improve public image	+1		+1	+1		+1	+1			+2		+1		

Legend
+ Positive factor (greater numerical value indicates increased emphasis)
– Negative factor (greater numerical value indicates increased emphasis)

Large-scale dynamics

The four reasons most commonly identified by fleet managers as to why they purchased an EV were testing new technologies, lowering their environmental impact, improving the organization's public image, and government grants. Of these, interviewees emphasized testing new technologies more than any other factor as being influential in their adoption decisions. In a related comment, the fleet manager from Firm 4 said “people that are immersed in auto technology might be more willing to evaluate something for technology's sake than the average consumer”.⁴⁶ And while many fleet managers were not willing to invest heavily in EVs, they were interested “to gain practical information about the performance and usability of electric cars” (Firm 6). The propensity of fleet managers to test new technologies and their willingness to act on those inclinations supports theoretical expectations from the literature and empirical evidence that organizations will be early EV adopters (Nesbitt and Sperling, 1998; Frost and Sullivan, 2013).

Additional and less important reasons for EV adoption, as identified by fleet managers, included lowering the organization's environmental impacts and improving its public image, which were often seen as being connected factors. While most fleet managers seemed to be genuinely focused on reducing their emissions levels, a small number of organizations adopted EVs specifically to “say that they did” (Firm 4) in what is commonly known as greenwashing (Ramus and Montiel, 2005). In those situations, organizations did not indicate intent to adopt a large number of EVs, but rather used the automobiles to emphasize that they were a green and eco-friendly firm.

Although fleet managers are always considering the financial impact of their vehicle purchase decisions (Nesbitt and Sperling, 1998), there was a sense that they were willing to pay an extra amount in order to adopt EVs. Even so, eight of the 14 organizations relied on

⁴⁶ Additional exemplary quotes from the different textual categories are noted in Table 3, providing a qualitative perspective that is not available in Table 6-2.

government grants in order to help overcome the uncertainty of using a new technology and also the vehicles' high purchase prices. Government grants were seen not as a reason to buy an EV, but rather as a measure which facilitated other goals such as testing new technologies or lowering emissions. This situation casts doubt on whether many of the fleet managers in this study would have adopted EVs without financial support from public policies.

Table 6-3: Exemplary quotes from textual categories

Textual category	Exemplary quote
Total ownership cost	<i>Electricity is cheaper than gasoline, and the expectation is that (EVs) will have lower maintenance costs than ICEVs. But this does not compensate for the high purchase costs: the total cost of ownership is at this time higher. (Firm 2)</i>
Fixed routes	<i>We chose (EVs) for routes where the vehicle could work based on the battery's charge. (Firm 10)</i>
Central refueling	<i>We built and use our own charging infrastructure. (Firm 9)</i>
First mover advantage	<i>Factor #1 is to be the first mover. That is the primary goal. (Firm 14)</i>
Lower environmental impact	<i>For us, sustainability is the most important success factor. We decided to spend more money for a cleaner car. (Firm 9)</i>
Govt. regulation	<i>We have a wave of (EVs) partly because of this rule. (Firm 4)</i>
Govt. grant	<i>The (EVs) were bought because we got a grant for it. (Firm 5)</i>
Test new technologies	<i>We were curious, and we also wanted to get experience with EVs. (Firm 3)</i>
Improve public image	<i>People want to be sustainable, so they chose us over other taxi companies. In terms of marketing, EVs are also an advantage. (Firm 7)</i>

Firm-specific factors

In addition to the broad dynamics identified above, there were also firm-specific issues that influenced fleet manager decisions regarding EV adoption, including whether the organization was public or private. In two instances, government agency decisions were driven partly by state-wide regulations. For those firms, legislation limited the number of ICEVs that public departments could purchase; however, this rule did not apply to EVs. Even though the fleet managers would have preferred to purchase ICEVs, they were still able to fulfill some of their departments' transportation needs through EVs. As this legislation only applied to governmental agencies, it did not influence private firm EV adoption. Businesses, on the other hand, were often driven by separate factors, citing first-mover advantage as an important reason why they adopted EVs, even if this forced them to take an initial financial loss. The importance of profit motive was influential in private firm EV adoption decisions, through the desire for first-mover advantages or the usefulness of EVs in improving the company's public image.

EV fleet expansion

Organizations were willing to initially purchase an EV to understand how the new technology performed relative to their operational needs. After a period experimenting with those automobiles, interviewees commonly declared that even though there was fuel savings, EVs on the whole were more expensive than ICEVs. Based purely on costs, most fleet managers were discouraged from buying additional EVs until the initial price point decreased substantially. However, EVs do not compete with ICEVs only on cost, but also offer a host of other benefits. As an indication of the importance of these factors, at least half of the firms in the study indicated an interest in expanding their EV fleets, which is remarkable considering

their high purchase costs. For those firms, this decision to buy additional EVs signified moving beyond a technological testing phase to a more permanent and widespread incorporation of the automobiles, “one important conclusion of this trial is that large-scale use of EVs seems feasible and the targeted percentage for 2015 is also within reach” (Firm 6). Tables 6-4 and 6-5 show the factors that influenced organizations as they decided whether or not to expand their EV fleets.

Table 6-4: Influential factors for organizations that expanded their EV fleets

Textual categories	Firm 1	Firm 4	Firm 6	Firm 7	Firm 9	Firm 12	Firm 14
Low operational costs			+3				
New performance capabilities	+3	+3					
First mover advantage				+3		+3	+3
Lower environmental impact		+2	+3	+2	+3		
Government regulation		+3					
Improve organization's public image	+1		+1	+1			+2

Legend
+ Positive factor (greater numerical value indicates increased emphasis)

Table 6-5: Influential factors for organizations that did not expand their EV fleets

Textual categories	Firm 5	Firm 8	Firm 10	Firm 13
Too much time lost during charging		-3		
Driving range lower than expected	-1	-2		
Not a viable business model	-3	-3	-3	-3
Lack of operational capabilities	-3		-1	

Legend
– Negative factor (greater numerical value indicates increased emphasis)

Tables 6-4 and 6-5 show that seven of the organizations chose to purchase additional EVs while four did not expand their fleets. Three firms were not included in these tables because they were still undecided as to their future EV adoption plans at the study’s conclusion. All of the organizations that decided not to adopt additional EVs indicated that the automobiles were not part of a viable business model, pointing to the primacy of finances in fleet management decisions. “After extensive testing, it was found that the current generation of EVs is not profitable as taxis” (Firm 8). Of the firms that did express an interest in expanding their EV fleets, there was no one overarching reason for this decision. Instead, these organizations’ decisions can be strongly connected to one of the following influential factors: it is a big firm pursuing first mover advantage, the EV performs a niche function, or the firm was able to develop an appealing business model. The attitudes and preferences of important individuals within the firm (not always the fleet manager) were also found to play an important role in the organization’s stance toward EV adoption.

There was a notable difference between the factors that influenced the EV adoption decisions of small and big private firms. While both types of businesses attempted to capture first-mover advantages, the economic losses associated with providing EV services were enough to discourage small firms from further adoption while the larger companies had greater financial support to rely upon. As a result, three of the four organizations that chose not to expand their EV fleets were smaller independent companies. Conversely, the larger private firms were willing to accept losses in order to reap potential financial rewards in the future through first mover benefits, lowered environmental impacts, and an improved public image. For one carsharing business, it was found that customers were eager and willing to test EVs. However, this did not translate to a solid business case, because their base purchase price was three times more expensive than comparable ICEVs (Subcompact/Segment A size).

Two organizations also found that EVs exhibited unexpected benefits in performance capabilities which supported their further adoption. This occurred when companies used an automobile in electric-only mode to perform maintenance tasks, allowing for communication between the individual in a bucket truck⁴⁷ and co-workers on the ground. This type of interaction was previously impossible over the noise of an internal combustion engine. Although this example represents a niche market, both companies that used hybrid bucket trucks emphasized the value of this feature and their interest in buying additional vehicles with this functionality.

Two other firms found EVs to be financially beneficial. In those situations, the fleet managers determined that their organization could either be profitable or achieve significant savings through using EVs. One organization calculated a payback period of seven years using governmental discounts on purchase price and energy costs. The other firm was able to find consumers willing to pay a premium for EV services. While these cases were in the minority, perhaps they point to novel and successful business models. If companies can develop successful business models centered on EVs, then their use and sales could increase substantially.

Finally, there were also examples where preferences of individuals played an important role in an organization's EV adoption decision. In a couple instances, fleet managers' negative experiences with new powertrains made them skeptical about adopting EVs. For those fleet managers, "the desire to experiment with alternative fuels generally took a back seat to certainty about vehicle performance" (Firm 1). Those organizations did purchase EVs because of government grants, but were hesitant to expand their fleets. Conversely, an enthusiastic executive or fleet manager was often the driving force behind expanding an organization's EV fleet even in the face of their higher costs relative to ICEVs.

6.5. Conclusions

This study employed empirical data identifying factors which influenced fleet manager adoption of EVs in an effort to update theory and provide testable propositions. Results determined that testing new technologies was the strongest driver of initial EV adoption, followed by lowering environmental impacts, governmental grants, and improving the organization's public image. There were also important firm-specific factors stemming from whether an organization was public or private; the decisions of several government agencies were affected by restrictive legislation, while profit-seeking companies identified potential

⁴⁷ These trucks use a bucket on an extendable mechanical arm from which a person can perform maintenance, such as trimming trees or repairing power lines.

financial benefits from first-mover advantage as having a powerful impact on their decision to adopt EVs.

Seven of the 14 organizations in the study chose to expand their EV fleets. However, for these firms there was no single overarching factor which drove this decision. Instead, the primary motivating rationales were firm-specific including pursuing first-mover advantage, specialized operational capabilities, and a compelling business model. The four firms that decided not to expand their EV fleets all cited the lack of a viable business model.

These results extend our understanding about EV adoption by fleet managers. Earlier studies looked at a broad set of consumers and noted the following reasons why organizations are more likely than households to be early EV adopters: their high vehicle purchase rates, intense usage, (frequently) centralized refueling stations, and limited number of decision makers. This article moves beyond identification of which type of consumers is likely to purchase the first EVs to analyzing the individual factors driving their decisions. As a result, it provides additional insight into the EV market through a better awareness of the issues which influence an important group of early adopters (fleet managers).

A broad conclusion that can be drawn from this research is that the first wave of EVs is generally a money losing venture for organizations. Some fleet managers were able to justify these expenses through non-financial benefits, specifically to test new technologies, leading to EV adoption. Thereafter, organizations that decided to expand their EV fleets did so for more firm-specific reasons. Based on this study, the following hypotheses are suggested for additional deductive research using broad statistical analyses:

- *Most organizations are early EV adopters to test the technology.*
- *Organizations expand their EV fleets for firm-specific reasons.*

6.5.1. Policy recommendations

Policy makers that want to support EV diffusion are recommended to encourage organizations to experiment with the automobiles. This could be accomplished either by providing EVs for testing (potentially through pilot projects), or removing barriers that currently discourage adoption e.g., technological uncertainty, high purchase price, and a lack of charging infrastructure. Government policies such as educational programs and financial incentives designed to eliminate these obstacles should lead to an increase in the number of firms that purchase an EV for trial purposes. As testing new technologies implies a low volume of vehicles per organization, initial fleet manager behavior may not result in them being heavy adopters during early EV commercialization. However, as this research identifies, some of these organizations will likely choose to expand their EV fleet after the initial testing phase, which will raise overall adoption rates as the vehicles are used more broadly throughout their operations.

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7. Conclusions

7.1. Revisiting the thesis setup

7.1.1. Background and research question

The introduction chapter of this thesis noted that the automobile industry faces an increasing level of uncertainty due to factors such as climate change, depletion of oil, and dependence on potentially unfriendly foreign regimes for fuel. Electric vehicles (EVs) have emerged as one of the most promising innovations to fundamentally address these issues in the long-term. However, substantial barriers to wide-spread EV diffusion have arisen from the need for firms to build new technological expertise, a lack of charging infrastructure, higher purchase costs, a lower driving range relative to ICEVs, and a required change in consumer behaviour. As governments and private firms draft their automobile policies, they will rely on existing research about the way in which different dynamics affect EV market introduction.

However, within that literature there is a lack of empirical understanding relating to factors that influence EV development and adoption. To this point, those factors have generally been identified and analyzed using stated preference (SP) studies⁴⁸ or theoretical extrapolations from other industries. Thus, the current understanding of EV commercialization is largely based on theory with little or no empirical testing. Furthermore, SP analysis may not represent actual consumer behaviour because individuals' values (which are captured by SP surveys) have been shown not to correspond to actual adoption of low-emissions vehicles, in a phenomenon known as the attitude-action gap (Lane and Potter, 2007).

Resulting from that gap in the literature, the goal of this thesis was to better understand the dynamics which underpin EV production and market introduction from the automotive industry's perspective. As such, this thesis set about to answer the following main research question, *how has the automotive industry approached the development and commercialization of EVs?* The emergence of EVs has been an extremely complicated period, and much too broad to be addressed in a single PhD thesis. Therefore, this study

⁴⁸ Stated preference studies are useful in instances where revealed preference data is not available. For example, to project expected demand for a technology that is not yet commercially available. However, once consumers have adopted that technology, studies revealed preference data are preferable.

primarily focused on the role of the automotive industry in that process. The research question above sought to analyze how specific actions by automobile manufacturers including their development of prototypes and collaboration with other firms have influenced the commercial emergence of EVs.

7.1.2. Study goal relative to academic and societal audiences

This study's goal offers contributions from both an academic and social perspective. Academically, it used empirical data to test several theories that have emerged regarding EV commercialization. Once the automobiles were commercially available, it became possible for researchers to empirically analyze important dynamics including what type of EVs were introduced commercially and what the effects of financial incentives on adoption were.

Socially, by using empirical data to examine influential dynamics, this thesis offers a more reliable guide for public policies and firm behavior. Governments or private firms that use such evidence-based analysis as a foundation for their actions will have a better grasp of relevant factors, which will likely result in more efficient use of resources and a more effective transition to wide-spread EV adoption.

7.1.3. Relationship between chapters

Thesis chapters were positioned to analyze several important dynamics between the following actors: auto manufacturers (both existing and new), firms from related industries e.g., battery and materials, government agencies, and consumers. In doing so, it looked at how three different stages of innovation (knowledge development, applied science, and adoption) relate to the commercial emergence of EVs.

For knowledge development, the thesis analyzed the way in which auto manufacturers collaborated with other organizations as they sought to build the expertise necessary for EV development. Thereafter, it investigated the applied science phase by looking at how incumbent (existing) firms approached the development of prototype and production EVs within a broader alternative fuel vehicle (AFV) paradigm. Then it zoomed in on the EV industry and showed the approaches taken by incumbent and startup auto manufacturers relative to development of different types of prototype and production models. Next, the thesis shifted its analytical focus to the adoption phase by examining how country-level socio-economic factors, specifically financial incentives, affected EV uptake. Continuing to examine the adoption phase of innovation, it analyzed the factors that influenced fleet managers' (a very important group of early adopters) decisions to purchase EVs.

7.2. Summary of chapter analysis

The thesis contained several chapters which analyzed different aspects of EV development and commercialization. The following subsections provide high-level summaries of the main findings for each chapter in addition to conclusions relative to their related research questions.

7.2.1. Auto manufacturer acquisition of expertise through alliances

Chapter 2 addressed the following research question, *how have auto manufacturers approached the acquisition of knowledge from disparate industries in order to produce a commercial EV?* Alliance formation theory indicates that during the early stage of innovation development firms will primarily form collaborations based on an explorative (developing

new knowledge) as opposed to exploitative (using existing expertise) relationships. In contrast to these studies, this thesis found that auto makers forged a large percentage (44%) of exploitative alliances during pre and early commercialization periods. In agreement with other studies, it found that incumbent manufacturers formed a greater number of alliances than did startups (twice as many), providing them with a competitive advantage and indicating the value of their greater resource levels. Manufacturers displayed distinct alliance formation patterns within key knowledge domains e.g., batteries and electric motors, preferring explorative collaborations in areas of expertise where they would like to have core competencies. However, the large number of exploitative alliances that manufacturers formed indicates that they developed collaborations to simultaneously pursue both commercialization and knowledge acquisition. This approach allows manufacturers to use exploitative alliances to bring EVs to market quickly while at the same time investing in explorative alliances to establish the necessary expertise in-house so that they could create the next generation of the automobiles on their own.

7.2.2. Incumbent manufacturer development of alternative fuel vehicles

In this chapter the primary research question was, *how have incumbent auto firms approached the development of EVs relative to other alternative fuel vehicles?* Results showed that during the 1991-2011 timeframe, auto manufacturer annual AFVs development increased 5 fold and doubled in technological variety (as measured by the fuel type used in vehicle powertrains e.g. hydrogen, electricity, and ethanol). For example, whereas in the early 1990s firms primarily focused on creating vehicles that ran on electricity or hydrogen, in the late 2000s they were *also* developing AFVs that used ethanol, compressed natural gas (CNG), or a combination of alternative fuels. This suggests that auto manufacturers are uncertain which powertrain will be successful in the future and want to be ready for any eventuality. Consequently, it appears that the automotive industry is becoming increasingly uncertain and turbulent, similar to the environment seen during the transitional 'era of ferment' phase of the technology cycle. As such, a technological transition might be underway resulting in the emergence of a new dominant automobile design. Since 2007, EVs and hybrid-electric vehicles (HEVs) have emerged as the most commonly developed AFV prototypes. Thus, there is an increasing level of momentum for those powertrains which could translate to them coming to the fore relative to the other AFV designs.

7.2.3. Technological diversity in the emerging EV industry

Chapter 4 examined *to what extent did incumbent and startup firms develop a variety of different EV types based on size and performance criteria?* Building upon the study above, the results from this article found that the EV industry is displaying several additional characteristics seen during a transitional era of ferment including an increase in firm entry, expansion of technological variety (based on battery chemistries), and exploration of niche markets. Throughout the 1990s, EV prototype and production models were primarily developed by large incumbent manufacturers such as Toyota, Volkswagen, and General Motors. Starting around 2004, that trend was upended with startups building the majority of new EV models (mostly prototypes). Companies devoted an increasing amount of resources to the automobiles as the number of firms that presented an EV model to the public increased from one in 2003 to 76 in 2011. Technological variety also shifted in the post 2004 time period with Lithium cathodes replacing Nickel-based configurations as the most commonly used EV batteries. Finally, the vehicles themselves saw a change as firms began targeting niche markets through the development of low speed vehicles (top speed of ~ 25 mph), 3-wheeled vehicles, sports cars, and mini automobiles e.g., Smart's Fortwo. In reference to this

last change, incumbent and startup auto manufacturers have taken two distinctive approaches to the EV market. Incumbent manufacturers predominantly developed EVs that matched the size and performance (top speed) characteristics of mass-marketed ICEVs; examples include the Nissan Leaf and Tesla Model S. Startups, on the other hand, developed EVs in all classes and performance ranges, but were characteristically different from incumbent firms in their exploration of niche markets. Of additional note is the lack of success that startup firms, excluding Tesla, have had in selling EVs. Through 2011, almost all EVs sold were built by incumbent manufacturers and resembled conventional ICEVs in size and top speed.

7.2.4. The influence of financial incentives and other factors on EV adoption

The research question of Chapter 5 was, *to what extent do financial incentives and other socio-economic factors (charging infrastructure, environmentalism, fuel cost, the presence of EV manufacturing facilities, income, education, vehicles per capita, electricity cost, model availability, EV price, and urban density) explain national EV adoption rates?* Financial incentives, the number of charging stations (corrected for population), and the presence of a local EV manufacturing facility were positive and significant in estimating EV adoption rates for the countries in our study. Of those variables, charging infrastructure was the best predictor of a country's EV market share. However, there was a great deal of heterogeneity in the correlation between national adoption figures and the level of financial incentives or charging infrastructure. Descriptive analyses indicated that country-specific factors such as government procurement plans or firm business model could have influenced this relationship and dramatically affected a nation's adoption rate. For example, in 2012 the Estonian national government decided to purchase 500 Mitsubishi MiEVs (up from 55 total adoptions in the country in 2011) and install an extensive fast charging network. This sudden influx of EVs and charging infrastructure caused Estonia to have the second highest adoption rate of all countries in our sample.⁴⁹ However, other countries did not experience such a large impact to EV adoption from government procurement. Relating to manufacturer influence in EV adoption, several companies e.g., Ford and Toyota, have had the highest level of vehicle sales in the country where their production facilities were located, suggesting a complex relationship between consumers, auto firms, and national attitude towards electric automobiles. In summary, EV-related factors such as charging infrastructure, financial incentives, and the presence of EV production facilities were discovered to be reliable predictors of adoption levels while broader socio-demographic variables such as income, education level, and environmentalism were not significant.

7.2.5. Influential factors in fleet manager adoption of EVs

The research question of Chapter 6 was, *what were the important factors that influenced fleet managers' initial adoption of EVs?* During their initial decision of whether or not to adopt an EV, fleet managers were influenced by a wide variety of factors including the desire to test new technologies, lower environmental impacts, availability of governmental grants, and an interest in improving the organization's public image. Of those, testing new technologies was the strongest and most prevalent factor in encouraging organizations to adopt EVs. There were also important dynamics stemming from whether an organization was public or private; the decisions of several government agencies were affected by restrictive legislation, while profit-seeking companies identified potential financial benefits from first-mover advantage as having a powerful impact on their EV adoption decision. When they were deciding whether or not to expand their number of EVs, fleet managers largely made their choice based on

⁴⁹ Removing Estonia from our model did not change the results.

firm-specific factors including first-mover advantage, specialized operational capabilities, or a compelling business model. A broad conclusion that can be drawn from this research is that the first wave of EVs was generally a money losing venture for organizations. Some fleet managers were able to justify these expenses through non-financial benefits, specifically to test new technologies, leading to EV adoption. Thereafter, organizations that decided to expand their EV fleets did so for more firm-specific reasons.

7.3. Answering the main research question

Conclusions drawn from these chapters address the study's research question of how the automobile industry set about developing and commercializing electric vehicles. Results show that contributing factors include the way in which manufacturers have gathered relevant expertise, the types of automobiles they have developed, the dominance of incumbent auto firms, and where EVs have been commercially introduced. Below is a description of how these different elements contribute to a broader understanding of how auto manufacturers have approached the emergence of EVs.

As acquiring new expertise is crucial to radical innovation (Teece, 1986) and firms are increasingly partnering with external organizations that already possess this knowledge (Cassiman and Veugelers, 2006), alliance formation is very important for the development of EVs. Results from this analysis show that incumbent auto manufacturers have forged a greater number of EV alliances than have startups, and that this strategy allows them to build critical expertise in-house through explorative partnerships. This allows incumbent firms to develop EVs while still remaining close to their existing business model and experience base.

In addition to a dramatic rise in the number of EV prototypes, auto manufacturers have also developed an increasing number of bi-fuel vehicles that can run on gasoline/diesel as well as an alternative fuels e.g., electricity, CNG, or ethanol. This suggests that firms are taking an incremental approach to AFV development as opposed to a steadfast drive toward commercializing more radical technologies such as EVs or hydrogen fuel cell vehicles (FCVs). Thus, while auto manufacturers are devoting resources toward commercializing EVs and FCVs, these efforts are tempered by their simultaneous focus on developing AFVs closer to the existing ICEV dominant design e.g., HEVs and bi-fuel vehicles.

Startup firms developed a wide range of non-conventional EVs such as 3-wheeled, low-speed vehicles, or mini automobiles. Incumbent firms, conversely, have based their EV designs on the size and performance expectations of ICEVs. To date, incumbent manufacturers have accounted for the vast majority of EV sales. Thus, the emerging EV industry remains strongly tied to the existing automobile paradigm relative to participating manufacturers and size/performance vehicle characteristics.

Furthermore, while auto manufacturers are targeting early EV adopters across several countries, they have focused primarily on and had the most sales success in their native country e.g., Toyota in Japan, Ford in the US, and Renault in France. And though these are likely the easiest sales, they also indicate that firms are pursuing a limited EV worldwide rollout. Consequently, instead of manufacturers making their EVs widely available in countries around the world, reduced distribution channels will likely result in lower EV adoption levels.

These results identify that although the automotive industry has pursued a strategy of exploring EV opportunities, firms have generally stayed connected to their relative experience base and business model. This reflects a gradual and measured approach to EV

development instead of a more aggressive attitude that would be favoured by startup firms that only produce electric automobiles. Based on the findings in this thesis, its primary conclusion is that a transition to EVs will be slow if it happens at all.

7.4. Significance of thesis conclusions

Because this thesis analyzes an eco-innovation that is just being introduced to the market, conclusions drawn from its results are applicable to both academic and social groups. Academically, it offers results from empirically tested theory. Socially, it provides insight into dynamics which affect the development and adoption of EVs, a technology that has the potential to dramatically reduce greenhouse gas emissions and urban pollution.

7.4.1. Academic relevance

This thesis contributes to theory relative to EV commercialization, eco-innovation, and innovation in general. Its contributions to EV theory include a better understanding of how firms pursued knowledge acquisition for developing the automobile innovation, both in-house as well as through partnerships. And by analyzing the roles of different types of manufacturers in EV market introduction, it showed that the process is largely incumbent driven. Regarding eco-innovation, the primacy of financial motives over environmental concerns for consumers was supported through fleet manager interviews. Also, analysis demonstrated that technological variety is richer in AFVs than in the EV industry.

More broadly, the thesis provides some insight into general innovation theory which depicts an era of ferment as a tumultuous period when a radical innovation emerges in a market. Results confirmed that the automobile industry has experienced an increase in several dynamics consistent with an era of ferment, including technological diversity, uncertainty, and firm entry. However, two of these factors (technological diversity and firm entry) have not been very influential in EV development and adoption. In that regard, this period has not been as turbulent as those found in other technological transitions. Consequently, these results contribute to the identification of influential factors across technological transitions through a better grasp of the role of startups and technological diversity in EV market introduction.

7.4.2. Societal relevance

From a societal perspective, this thesis should be read not as full-throated support for EVs as the future of sustainable automobility, but rather as cautious optimism of the innovation's prospects. The recent rapid increase in charging infrastructure, available production models, and sales indicates that EVs do have a degree of market momentum. However, incumbent auto manufacturers may be hesitant to invest in EV development and introduction, specifically compared to startups that only sell electric automobiles. Therefore, additional efforts are likely to be necessary if the goal is to assist and accelerate a technological transition. These include increasingly stringent emissions regulation, charging infrastructure, financial incentives, and educational campaigns to address consumer (mis)perceptions about EVs.

While research and development of EVs should continue, policy makers are recommended against viewing that technology as the inevitable destination for sustainable automobility. Even though radical technologies such as FCVs and EVs may offer the most dramatic improvements in individual automobile emissions, incremental advances also provide the opportunity for substantial gains. For instance, hybridization, lightweighting, and

improvements in technological efficiency leveraged across a large number of vehicles could lead to greater decreases in emissions than a small number of EV or FCV adoptions. Instead of focusing on a single technology, policy makers ought to devote resources to developing a wide set of options.

Therefore, a prudent policy approach would be to use broad emissions regulation to incrementally lower emissions from a large number of vehicles while supporting the development of more radical innovations through measures such as financial incentives, R&D grants, and pilot projects. One important element of such a policy is the need to be adaptive. The automobile industry is currently subject to great uncertainty for several reasons. Technological change such as hydraulic fracturing (providing cheaper and more plentiful natural gas) or improvements in battery density have quickly altered the lifetime cost structure for AFVs. In addition, geopolitical activity including wars (or the threat thereof) as well as regime change have in the past (and can again in the future) led to a dramatic and swift impact on the price for vehicle fuels, specifically those derived from oil. These dynamics, combined with more incremental social transformation e.g., an increasing global demand for automobile transportation and the push to reduce greenhouse gas emissions, provide a landscape that is rapidly changing.

Therefore, policy needs to be adaptive in order to support the correct innovations. An example of how policy can be adaptive is to make it technology-neutral. For example, consumer subsidies can be based on vehicle emissions, regardless of whether the automobile uses an ICE, hybrid, EV, or hydrogen powertrain. Also, a portion of basic research grants and subsidies could be used to target particularly promising innovations; these could change from year to year depending on which technology has the greatest potential.

Recommendations for further research

Because few firms are exclusively producing and promoting EVs, the current incumbent-dominated environment could have lasting and extensive knock-on effects for the innovation's introduction and potential for wide-spread commercial adoption. Specifically, this dynamic will likely result in slowing a technological transition to EVs because incumbent auto manufacturers are still devoting extensive resources to developing ICEVs and AFVs closer to this dominant design, and may fear cannibalization of their existing customer base. Further research could analyze the way that incumbent development of ICEVs or different types of AFVs affects EV adoption levels.

Possible research questions include to what extent is the lack of startup EV firms slowing or influencing a potential technological transition? In addition, as a broader range of AFVs come to market e.g., FCVs, how do manufacturers allocate resources between the competing technologies, and how does this influence EV adoption?

It might also be worthwhile to analyze the commercialization of EVs relative to other technological transitions where startups and technological diversity have played a greater or lesser role. This could provide historical evidence for which factors will be particularly influential during the current EV market introduction.

7.4.3. A parting thought . . .

A key issue is whether industrial dynamics such as learning by doing and scale economies can improve EV price and performance characteristics such that they become appealing to the much bigger and conservative group of early majority adopters. That, along with government

willingness to continue offering financial incentives for EV purchases will be crucial in determining whether the innovation moves out of its niche market to be a more established player in the automotive landscape. And while the media and government agencies correctly identify that EVs are rapidly gaining momentum, a technological transition to that innovation is hardly assured.

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Appendices

Appendix A: Assumptions for Table 1-1

Vehicles used in calculations

ICEV	2012 Ford Focus
EV	2012 Nissan Leaf
FCV	Honda FCX Clarity
CNG	2012 Honda Civic CNG
Ethanol	2013 Ford Focus FFV
Hybrid	2012 Toyota Prius C

Fuel Prices used in calculations

Gasoline	\$3.65/gallon
Electricity	\$0.144/kWh
Hydrogen	\$4.49 per kg
Compressed natural gas	\$0.0169/cubic foot
Ethanol (E85)	\$3.23/gallon

Annual fuel costs based on 12,000 miles driven (44% city and 56% highway)

References: (Spath and Mann, 2001; US Census, 2013; US News, 2013; US DoE, 2012; US DoE, 2013a; US DoE 2013b)

Appendix B: Characteristics of midsize alternative fuel vehicles in metric (based on US data)

Vehicle	2012 price	Annual fuel costs	Fuel economy (km per gallon)	Fuel emissions (lbs. CO ₂)	Range (km)	Fueling time	Fueling stations
ICEV	\$16,500	\$1,416	41 city/57 hwy	9,605	598	4 min	121,000
EV	\$35,200	\$600	207 city/164 hwy	7,894	117	30 min	6,806
FCV	\$600/month ⁵⁰	\$898	98 city/98 hwy	3,792	386	4 min	10
CNGV	\$26,305	\$793	43 city/61 hwy	8,292	354	4 min	632
FFV	\$17,996	\$1,620	32 city/45 hwy	10,464	460	4 min	2,354
HEV	\$18,950	\$891	85 city/74 hwy	6,042	735	4 min	121,000

Appendix C: List of abbreviations

Al	Aluminum
C	Carbon
CARB	California Air Resources Board
CFL	Compact Fluorescent Lamp
Co	Cobalt
EU	European Union
EV	Electric Vehicle
Fe	Iron
HCV	Heavy Commercial Vehicle
HEV	Hybrid-Electric Vehicle
ICE	Internal Combustion Engine
KBA	German Federal Transport Authority
kWh	Kilowatt Hour
LCV	Light Commercial Vehicle
Li	Lithium
LSV	Low Speed Vehicle
Mn	Manganese
MPV	Multi-Purpose Vehicle
Ni	Nickel
O	Oxygen
P	Phosphate
PSA	Peugeot Citroen
SUV	Sports Utility Vehicle
Ti	Titanium
UK	United Kingdom
US	United States
V	Vanadium
ZEV	Zero Emissions Vehicle

⁵⁰ The Honda FCX Clarity is currently only available for lease, so a purchase price comparison is not possible.

Appendix D: Correlations between model variables

	Market share	Incentive	Env	Fuel	Chg infra	HQ	Income	Per cap vehicles	Ed	Elec	Avail	EV intro	EV price	Urban density
Mar share	1	,498**	.258	-.091	,697**	,400*	,443*	.142	.347	.089	,375*	,553**	-.448*	-.277
Incentive	,498**	1	-.115	-.015	,380*	-.058	.135	-.111	,366*	.112	-.141	.130	-.311	-.139
Env	.258	-.115	1	.182	.260	.048	,586**	,565**	.048	.304	,423*	,375*	-.380*	-,477**
Fuel	-.091	-.015	.182	1	.107	-.183	-.081	-.141	-.263	.082	-.136	-.159	.282	,433*
Chg infra	,697**	,380*	.260	.107	1	.011	,455*	-.049	.213	.065	.259	,447*	-.361	-.135
HQ	,400*	-.058	.048	-.183	.011	1	.163	.036	.042	.085	,524**	,492**	-.133	-.043
Income	,443*	.135	,586**	-.081	,455*	.163	1	,647**	,514**	.313	,403*	,559**	-.461*	-,622**
Per cap veh	.142	-.111	,565**	-.141	-.049	.036	,647**	1	.320	.241	.174	.250	-.336	-,739**
Ed	.347	,366*	.048	-.263	.213	.042	,514**	.320	1	.002	-.117	.053	-.419*	-,392*
Elec	.089	.112	.304	.082	.065	.085	.313	.241	.002	1	,463**	.274	-.065	-.200
Avail	,375*	-.141	,423*	-.136	.259	,524**	,403*	.174	-.117	,463**	1	,542**	-.201	-.235
EV intro	,553**	.130	,375*	-.159	,447*	,492**	,559**	.250	.053	.274	,542**	1	-.391*	-.247
EV Price	-.448*	-.311	-,380*	.282	-.361	-.133	-.461*	-.336	-.419*	-.065	-.201	-.391*	1	,448*
Urb Den	-.277	-.139	-,477**	,433*	-.135	-.043	-,622**	-,739**	-,392*	-.200	-.235	-.247	,448*	1

**Significant at the 0.01 level (2-tailed).

*Significant at the 0.05 level (2-tailed).

Summary

Background

In order to help address concerns stemming from climate change, dependence on unpredictable autocratic regimes for fuel, and depletion of finite oil resources, governments around the world have implemented stringent regulations on vehicle emissions and fuel economy. The combination of these regulations along with auto manufacturer development of new powertrain technologies indicates an increasing level of uncertainty in the automobile industry and that a transitional period in automobility could be underway. The electric powertrain is one innovation that has emerged with the potential to dramatically reduce greenhouse gas (GHG) emissions from the transportation sector in the post-2020 timeframe. However, electric vehicles (EVs) only became widely available for adoption in 2010 (not including the failed attempt at their commercialization in the 1990s). And due to the subsequent lack of real-world empirical data, there is limited understanding of how different factors influence their development and adoption, hindering the ability of actors to encourage a rapid transition to broad EV use.

Some of the key factors which will determine EV adoption levels include how the innovation compares technically to existing internal combustion engine vehicles (ICEVs) and other alternative fuel vehicles (AFVs). As of 2014, most mass-market EVs (not including the Tesla Model S) employ Lithium-Ion batteries, cost roughly \$25,000-\$40,000, and have a 75-100 mile driving range. Because EVs use electricity instead of gasoline or diesel, they emit 10-24% lower levels of GHGs, depending on power grid mix, speed and load conditions, and total miles driven (Hawkins et al., 2012; Ma et al., 2012). Vehicle charging time can vary from 30 minutes to several (>10) hours depending on the outlet voltage (500v and 110v respectively). And while charging stations have multiplied over the past few years, their number still accounts for less than 6% of available gasoline stations in the US. Limited charging infrastructure is often dubbed the *chicken or egg* problem (Struben and Sterman, 2008). Consumers do not want to purchase an EV without ample available charging stations, and organizations (public and private) do not want to invest in building such infrastructure until there is a sufficiently large market.

Manufacturers are developing many different types of AFVs and making them available for purchase including: hybrid-electric vehicles (HEVs), hydrogen fuel cell vehicles (FCVs), compressed natural gas vehicles (CNGVs), and flex fuel vehicles. Compared to these alternatives, EVs are more expensive, have lower annual fuel costs, better fuel economy, lower GHG emissions, a significantly smaller driving range, a longer fueling time, and generally more refueling stations (but not anywhere near as many as ICEVs) (Spath and Mann, 2001; US Census, 2013; US News, 2013; US DoE, 2012; US DoE, 2013a; US DoE 2013b).

In addition to these technical issues, there are several broader theoretical factors which influence EV development and adoption. Because ICEVs have largely been unchallenged over the past 100 years, the technology has experienced continuous incremental improvements in many areas including engine efficiency, safety, and comfort as well as the development of a support system e.g., maintenance and refueling stations. Through technological and institutional positive feedback mechanisms, the ICEV has become the dominant automobile design. Replacing a dominant design is a difficult proposition, specifically because radical innovations do not have a long history of incremental improvements or economies of scale. Also, when innovations employ dramatically different technology (such as the electric motor and battery in the EV case), they are associated with increasing levels of uncertainty which has a negative effect on consumer willingness to pay, future profitability, and government involvement. Furthermore, since consumers do not calculate total lifetime costs when purchasing an automobile, EVs have reduced adoption rates i.e., their high purchase costs often outweigh benefits from lower operating costs. A final barrier to EV diffusion arises because consumers generally do not pay the full marginal costs for the pollution that their automobiles emit.⁵¹ If they did, ICEVs would be more expensive because consumers would have to pay for pollution emissions that damage individuals' health, leading to EVs having a better cost comparison and subsequently higher adoption levels.

There is a broad set of actors involved in EV commercialization including battery makers, energy providers, auto manufacturers, and consumers. In addition, government agencies also frequently play a role in this process to address market failures arising from externalities (specifically pollution). Uncertainty heavily influences the situation because actors do not know how quickly EVs will improve and whether they should develop/adopt/support that type of automobile as opposed to a different option such as FCVs or HEVs. Because of their importance, this thesis will primarily focus on the manufacturers who develop the automobiles, the end consumers who buy them, and government agencies that seek to influence this relationship.

Literature gap and research question

Researchers analyzing these technical and theoretical barriers have determined that EV adoption will be dramatically limited without stimulation from external forces such as stringent emissions regulations, rising fuel prices, or financial incentives. Consequently, auto manufacturers, policy makers, and researchers have concluded that the prospects for EV commercialization entail a high level of ambiguity.

This uncertainty encourages rigorous analysis by researchers of how different dynamics affect EV development and adoption. For example, there is concern that the existing EV literature may

⁵¹ This is a general note. Countries vary in their levels of emissions taxation.

not accurately reflect the current industrial environment because most studies analyzed *stated* as opposed to *observed* consumer behavior, or were conducted before the most recent commercialization effort. Due to the value-action gap (where an individual's answers on surveys do not match their actions), stated preference surveys may not correctly identify consumer behavior vis-à-vis EVs. Therefore, there are reasons to doubt whether survey studies correctly reflect how consumers will act toward the automobiles.

The thesis seeks to help fill this literature gap by focusing on the role that the automotive industry has played during EV market introduction and how different factors such as financial incentives, knowledge acquisition, and prototype development have influenced this period. And because EVs have been broadly available for purchase for a number of years, it is now possible to use empirical data in this analysis. This approach builds upon earlier research which employed stated preference studies, and addresses concerns from the value-action gap. The central research question of this thesis is:

How has the automotive industry approached the development and commercialization of electric vehicles?

To answer that question, the thesis uses a series of sub-queries which each occupy a single chapter of this volume. These individual studies are identified below along with their respective data and methods.

Data and methods

Because the emergence of a radical innovation such as EVs often coincides with a constantly changing market environment and increased uncertainty (termed an 'era of ferment' in the literature), it is important that analysis of these situations use the most current and reliable information. In this regard, individual studies employed proven collection methods when using publicly available sources (which often provide the most up-to-date data available). In order to address the main thesis research question, it was necessary to collect a broad set of data including manufacturer alliances, vehicle sales, public charging stations, and prototype/production models.

This thesis employed both inferential and descriptive analytical methods, including content analysis (both qualitative and quantitative), linear regression using ordinary least squares, t-tests, and frequency distributions. Because of the uncertainty involved in the emergence of a radical innovation, there is concern that statistical analyses may not correctly capture all of the relevant variables in a relationship. Therefore, statistical tests were complimented with descriptive analysis identifying where patterns did not hold and providing possible factors which played a role in these situations. Table 1 gives a high-level overview of the research question, data, and analysis of each thesis chapter. A more detailed description of the data used and analysis method employed can be found within the relevant chapter.

Table 1: Overview of research question, data, and methods by thesis chapter

Chapter	Research question	Data	Methods
2	<i>How have auto manufacturers approached the acquisition of knowledge from disparate industries in order to produce a commercial EV?</i>	Auto manufacturer alliances	T-test Binomial analysis Descriptive figures Content analysis
3	<i>How have incumbent auto firms approached the development of EVs relative to other alternative fuel vehicles?</i>	Alternative fuel vehicle prototype and production models	Descriptive figures
4	<i>To what extent did incumbent and startup firms develop a variety of different EV types based on size and performance criteria?</i>	Electric vehicle prototype and production models	Descriptive figures
5	<i>To what extent did financial incentives and other socio-economic factors explain national EV adoption rates?</i>	EV adoption rates Financial incentives Income, fuel costs, etc.	Linear regression Descriptive figures
6	<i>What were the important factors that influenced fleet managers' initial adoption of EVs?</i>	Fleet manager interviews	Content analysis Descriptive figures

Results

In contrast to earlier studies, **Chapter 2** finds that auto makers forged a large percentage (44%) of exploitative alliances during pre and early commercialization periods. In agreement with other research, it found that incumbent manufacturers formed a greater number of alliances than did startups (twice as many), providing them with a competitive advantage and indicating the value of their greater resource levels. Manufacturers displayed distinct alliance formation patterns within key knowledge domains e.g., batteries and electric motors, preferring explorative collaborations in areas of expertise where they would like to have core competencies. However, the large number of exploitative alliances that manufacturers formed indicates that they developed collaborations to simultaneously pursue both commercialization and knowledge acquisition. This approach allows manufacturers to use exploitative alliances to bring EVs to market quickly while at the same time investing in explorative alliances to establish the necessary expertise in-house so that they can create the next generation of the automobiles on their own.

Results from **Chapter 3** show that during the 1991-2011 timeframe, the number of AFVs that auto manufacturers developed annually increased 5 fold and doubled in technological variety (as measured by the fuel type used in vehicle powertrains e.g. hydrogen, electricity, and ethanol). For example, whereas in the early 1990s firms primarily focused on creating vehicles that ran on electricity or hydrogen, in the late 2000s they were *also* developing AFVs that used ethanol, CNG, or a combination of alternative fuels. This suggests that auto manufacturers are uncertain which powertrain will be successful in the future and want to be ready for any eventuality. Consequently, it appears that the automotive industry is becoming increasingly uncertain and

turbulent, similar to the environment seen during the transitional 'era of ferment' phase of the technology cycle. As such, a technological transition might be underway resulting in the emergence of a new dominant automobile design. Since 2007, EVs and HEVs have emerged as the most commonly developed AFV models. Thus, there is an increasing level of momentum for those powertrains which could translate to them coming to the fore relative to the other AFV designs.

Building upon the earlier chapters, the results from **Chapter 4** find that the EV industry is displaying several additional characteristics seen during a transitional era of ferment including an increase in firm entry, expansion of technological variety (based on battery chemistries), and exploration of niche markets. Throughout the 1990s, EV prototype and production models were primarily developed by large incumbent manufacturers such as Toyota, Volkswagen, and General Motors. Starting around 2004, that trend was upended with startups building the majority of new EV models (mostly prototypes). Companies devoted an increasing amount of resources to developing EV technology as the number of firms that presented a prototype or production model to the public increased from one in 2003 to 76 in 2011. Technological variety also shifted in the post-2004 time period with Lithium cathodes replacing Nickel-based configurations as the most commonly used EV batteries. Finally, the vehicles themselves saw a change as firms began targeting niche markets through the development of low speed vehicles (top speed of approximately 25 mph), 3-wheeled vehicles, sports cars, and mini automobiles e.g., the Smart Fortwo. In reference to this last change, incumbent and startup auto manufacturers have taken two distinctive approaches to the EV market. Incumbent manufacturers predominantly developed EVs that matched the size and performance (top speed) characteristics of mass-marketed ICEVs; examples include the Nissan Leaf and Tesla Model S. Startups, on the other hand, developed EVs in all classes and performance ranges, but were characteristically different from incumbent firms in their exploration of niche markets. Of additional note is the lack of success that startup firms, excluding Tesla, have had in selling EVs. Through 2011, almost all EVs sold were built by incumbent manufacturers and resembled conventional ICEVs in size and top speed.

Chapter 5 identifies that financial incentives, the number of charging stations (corrected for population), and the presence of a local EV manufacturing facility were positive and significant in estimating EV adoption rates for the countries in our study. Of those variables, charging infrastructure was the best predictor of a country's EV market share. However, even with strong correlation, there was a great deal of heterogeneity between national adoption figures and the level of financial incentives or charging infrastructure. Descriptive analyses indicate that country-specific factors such as government procurement plans or firm business model could have influenced this relationship and dramatically affected a nation's adoption rate. For example, in 2012 the Estonian national government decided to purchase 500 Mitsubishi MiEVs (up from 55 total adoptions in the country in 2011) and install an extensive fast charging network. This sudden influx of EVs and charging infrastructure caused Estonia to have the second highest adoption rate of all countries in our sample (removing Estonia from our model did not change its results). However, other countries did not experience such a large impact to EV adoption from government procurement. Relating to manufacturer influence in EV adoption, several companies e.g., Ford and Toyota, have had the highest level of vehicle sales in the country where their production facilities were located, suggesting a complex relationship between consumers, auto firms, and national attitude towards electric automobiles. In summary, EV-related factors such as

charging infrastructure, financial incentives, and the presence of EV production facilities were discovered to be reliable predictors of adoption levels while broader socio-demographic variables such as income, education level, and environmentalism were not significant.

Results from **Chapter 6** determined that during fleet managers' initial decision of whether or not to adopt an EV, they were influenced by a wide variety of factors including the desire to test new technologies, lower environmental impacts, the availability of governmental grants, and an interest in improving the organization's public image. Of those, testing new technologies was the strongest and most prevalent factor in encouraging organizations to adopt EVs. There were also important dynamics stemming from whether an organization was public or private; the decisions of several government agencies were affected by restrictive legislation, while profit-seeking companies identified potential financial benefits from first-mover advantage as having a powerful impact on their EV adoption decision. When they were deciding whether or not to expand their number of EVs, fleet managers largely made their choice based on firm-specific factors including first-mover advantage, specialized operational capabilities, or a compelling business model. A broad conclusion that can be drawn from this research is that the first wave of EVs was generally a money losing venture for organizations. Some fleet managers were able to justify these expenses through non-financial benefits, specifically to test new technologies, leading to EV adoption. Thereafter, organizations that decided to expand their EV fleets did so for firm-specific reasons.

Conclusions

Conclusions drawn from these studies address the thesis research question of how the automobile industry has set about developing and commercializing electric vehicles. Results show that contributing factors include the way in which manufacturers have gathered relevant expertise, the types of automobiles they have developed, the dominance of incumbent auto firms, and where EVs have been commercially introduced.

As acquiring new expertise is crucial to radical innovation and firms are increasingly partnering with external organizations that already possess this knowledge, alliance formation is very important for the development of EVs. Incumbent auto manufacturers have forged a greater number of EV alliances than have startups, a strategy allows the companies to build critical expertise in-house through explorative partnerships. Incumbent firms are thus positioned to develop EVs while still remaining close to their existing business model and experience base.

In addition to a dramatic rise in the number of EV prototypes, auto manufacturers have also developed an increasing number of bi-fuel vehicles that can run on gasoline or diesel as well as use an alternative fuel e.g., electricity, CNG, or ethanol. This suggests that firms are taking an incrementalist approach to AFV development as opposed to a steadfast drive toward commercializing a more radical powertrain innovation. Therefore, while auto manufacturers are devoting resources toward the market introduction of EVs and FCVs, these efforts are tempered by their simultaneous focus on developing AFVs closer to the existing ICEV dominant design e.g., HEVs and bi-fuel vehicles.

Startup firms developed a wide range of non-conventional EVs such as 3-wheeled, low-speed vehicles, and mini automobiles. Incumbent firms, conversely, have based their EV designs on the size and performance expectations of ICEVs. To date, incumbent manufacturers have accounted

for the vast majority of EV sales. Thus, the emerging EV industry remains strongly tied to the existing automobile paradigm relative to participating manufacturers and size/performance vehicle characteristics.

Furthermore, while auto manufacturers are targeting early EV adopters across several countries, they have focused primarily on and had the most sales success in their native countries e.g., Toyota in Japan, Ford in the US, and Renault in France. And though these are likely the easiest sales, they also indicate that firms are pursuing a limited worldwide rollout for EVs. Consequently, instead of manufacturers making their EVs widely available in countries around the world, the presently seen reduced distribution channels will likely result in lower EV adoption levels.

These conclusions identify that although the automotive industry has pursued a strategy of exploring EV opportunities, firms have generally stayed connected to their relative experience bases and business models. This reflects a gradual and measured approach to EV development instead of a more aggressive attitude that would be favoured by startup firms which only produce electric automobiles. Based on the above findings the primary conclusion of this thesis is that a transition to EVs will be slow if it happens at all.

Policy recommendations

From a societal perspective, this thesis should be read not as full-throated support for EVs as the future of sustainable automobility, but rather as cautious optimism of the innovation's prospects. The recent rapid increase in charging infrastructure, available production models, and sales indicates that EVs do have a degree of market momentum. However, incumbent auto manufacturers may be hesitant to heavily invest in EV development and introduction, specifically compared to startups that only sell electric automobiles. Therefore, if the policy goal is to accelerate a technological transition, additional efforts are likely to be necessary including increasingly stringent emissions regulation, adding charging infrastructure, offering financial incentives, and using educational campaigns to address consumer (mis)perceptions about EVs.

While research and development of EVs should continue, policy makers are recommended against viewing that technology as the inevitable destination for sustainable automobility. Even though radical technologies such as FCVs and EVs may offer the most dramatic improvements in individual automobile emissions, incremental advances also provide the opportunity for substantial gains. For instance, hybridization, lightweighting, and improvements in technological efficiency leveraged across a large number of vehicles could lead to greater decreases in emissions than a small number of EV or FCV adoptions. Instead of focusing on a single technology, policy makers ought to devote resources to developing a diverse set of powertrain options. Suggested policies include broad emissions-reduction regulation, consumer financial incentives focusing on decreasing automobile pollution, and basic R&D funding for particularly promising innovations.

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Samenvatting

Achtergrond

Om vraagstukken aan de orde te helpen stellen die voortkomen uit klimaatverandering, afhankelijkheid van onvoorspelbare autocratische olieproducerende regimes en uitputting van eindige oliebronnen hebben regeringen over de hele wereld strenge regelgeving geïmplementeerd op het gebied van uitstoot van voertuigen en het besparen van brandstof. De combinatie van deze regelgevingen en de ontwikkeling van nieuwe aandrijvings-technologieën door autofabrikanten is een indicatie voor een toenemende mate van onzekerheid in de automobielenindustrie, evenals voor het mogelijke begin van een overgangperiode in de mobiliteit. De elektrische aandrijving is een van de innovaties die naar voren is gekomen met de potentie om uitstoot van broeikasgassen van de transportsector dramatisch te verminderen in de periode na 2020. Elektrische voertuigen (EV's) zijn echter pas in 2010 op de commerciële markt gekomen (waarbij de mislukte poging voor commercialisering in de jaren 90 buiten beschouwing wordt gelaten). Omdat er dus gebrek aan empirische gegevens is, is er weinig kennis van hoe verschillende factoren ontwikkeling en acceptatie beïnvloeden, wat de mogelijkheid voor de markt om breed gebruik van EV's te stimuleren in de weg staat.

Enkele belangrijke factoren die acceptatieniveaus van EV's zullen bepalen, zijn hoe de innovatie zich technisch verhoudt tot bestaande voertuigen met verbrandingsmotoren (ICEV's) en voertuigen op alternatieve brandstoffen (AFV's). In 2014 gebruiken de meeste EV's in massaproductie (exclusief de Tesla Model S) lithium-ion-accu's. Ze kosten grofweg \$ 25.000-\$ 40.000 en hebben een bereik van 75-100 mijl. Omdat EV's elektriciteit gebruiken in plaats van benzine of diesel, stoten ze 10-24% minder broeikasgassen uit, afhankelijk van de elektriciteitsopwekking, de snelheid en overig rijgedrag, evenals het aantal gereden mijlen (Hawkins et al., 2012; Ma et al., 2012). Het opladen van een voertuig duurt ergens tussen 30 minuten en meerdere (>10) uren, afhankelijk van de netspanning (respectievelijk 500V en 110V). Hoewel er de afgelopen jaren veel laadstations zijn bijgekomen, is het totaal nog steeds minder dan 6% van de tankstations voor benzine in de Verenigde Staten. Een beperkte infrastructuur voor opladen wordt vaak het *kip-ei*-probleem genoemd (Struben and Sterman, 2008). Klanten willen geen EV kopen zonder voldoende beschikbare oplaadstations en

(overheids- en commerciële) organisaties willen niet investeren in het bouwen van een dergelijke infrastructuur tot de markt groot genoeg is.

Fabrikanten ontwikkelen veel verschillende types AFV's en brengen deze op de markt, zoals hybride voertuigen (HEV's), voertuigen op waterstof (FCV's), voertuigen op aardgas (CNGV's) en voertuigen die flexibel zijn qua brandstof. Vergeleken met deze alternatieven zijn EV's duurder, maar ze kosten jaarlijks minder aan brandstof, gebruiken minder energie en stoten minder broeikasgassen uit. EV's hebben een kleinere actieradius en het duurt langer om ze te laden dan dat tanken kost, maar doorgaans zijn er meer laadstations dan voor bijvoorbeeld waterstof (hoewel zeker niet zoveel als voor ICEV's) (Spath and Mann, 2001; US Census, 2013; US News, 2013; US DoE, 2012; US DoE, 2013a; US DoE 2013b).

Naast deze technische problemen zijn er verschillende andere factoren die theoretisch de ontwikkeling en acceptatie van EV's beïnvloeden. Omdat er de afgelopen 100 jaar nauwelijks concurrentie was voor ICEV's is de techniek doorlopend incrementeel verbeterd op vele gebieden, zoals motorefficiëntie, veiligheid en comfort. Dit geldt ook voor de ontwikkeling van de mogelijkheden voor onderhoud en voor tankstations. ICEVs zijn door middel van positieve feedback op het gebied van techniek en organisatie het dominante ontwerp voor de automobielindustrie geworden. Het vervangen van een dominant ontwerp is moeilijk, in het bijzonder omdat radicale innovaties geen lange geschiedenis hebben van incrementele verbeteringen of schaalvergroting. Wanneer innovaties daarnaast complete andere technieken gebruiken (zoals de elektrische motor en accu in het geval van het EV), worden ze geassocieerd met minder zekerheden, wat een negatief effect heeft op de bereidheid van klanten om hiervoor te betalen, en een negatief effect op de winstgevendheid van producenten in de toekomst, en overheden zijn minder betrokken bij EV's. Aangezien consumenten bovendien bij het aanschaffen van een auto de kosten van de totale levensduur niet berekenen, kopen ze minder vaak EV's; de hoge aankoopkosten wegen vaak zwaarder dan de lagere verbruikskosten. Wat ten slotte de laatste belemmering is voor EV's om te worden geaccepteerd, is dat klanten over het algemeen niet de volledige kosten betalen voor de vervuilende uitstoot van hun auto's.⁵² Als dat wel het geval zou zijn, zouden ICEV's duurder zijn omdat consumenten zouden moeten betalen voor vervuilende uitstoot, met als gevolg dat de kosten van EV's concurrerender zouden zijn, en vaker gekocht zouden worden.

Er zijn verschillende partijen betrokken bij commercialisering van EV's, zoals accuproducenten, energieleveranciers, autofabrikanten en consumenten. Daarnaast spelen overheidsorganisaties ook vaak een rol in het proces van marktpenetratie van EV's door marktfalen als gevolg van zogenoemde externe kosten (met name: vervuiling) te corrigeren door daar beleid voor te ontwikkelen. Onzekerheid heeft een grote invloed op de situatie omdat partijen niet weten hoe snel EV's zullen worden verbeterd en of ze een dergelijke auto moeten ontwikkelen/overnemen/ondersteunen. Dit in tegenstelling tot andere opties zoals FCV's of HEV's. Vanwege de belangrijke positie van de fabrikanten die de auto's ontwikkelen zal dit proefschrift zich ten eerste op hen richten, evenals op de consumenten die de auto's kopen en de overheidsorganisaties die deze relatie willen beïnvloeden.

Hiaat in literatuur en onderzoeksvraag

Onderzoekers die deze technische en theoretische belemmeringen analyseren, hebben vastgesteld dat draagvlak voor EV's ernstig zal worden beperkt zonder externe stimuleringen zoals strenge regelgeving betreffende uitstoot, stijgende brandstofprijzen of financiële

⁵²Dit is een algemene notie. Landen variëren in hoe zij het niveau emissiebelasting bepalen.

prikkels. Als gevolg hiervan hebben autofabrikanten, beleidsmakers en onderzoekers geconcludeerd dat de vooruitzichten voor commercialisering van EV's een hoge mate van onduidelijkheid met zich meebrengt.

Deze onzekerheid stimuleert onderzoekers grondig te analyseren hoe verschillende dynamieken de ontwikkeling en acceptatie van EV's beïnvloeden. Mogelijk geeft de bestaande literatuur met betrekking tot EV's de huidige industriële omgeving niet accuraat weer, omdat de meeste geanalyseerde onderzoeken het gedrag van consumenten *benoemen* in plaats van *in acht nemen*, of zijn uitgevoerd voorafgaand aan de meest recente poging tot commercialisering. Vanwege het hiaat tussen waarde en actie (waarbij de antwoorden van een persoon niet overeenkomen met zijn acties), identificeren de genoemde onderzoeken betreffende voorkeur het gedrag van consumenten met betrekking tot EV's mogelijk niet op correcte wijze. Daarom kan men zich afvragen of onderzoeken het consumentengedrag met betrekking tot EV's correct weergeven.

Dit proefschrift tracht dit hiaat in literatuur (deels) te dichten door zich te richten op de rol die de automobiellindustrie tijdens de introductie van EV's heeft gespeeld en op de vraag hoe verschillende factoren zoals financiële stimulans, het verkrijgen van kennis en de ontwikkeling van prototypes deze periode hebben beïnvloed. Aangezien EV's nu een aantal jaren breed verkrijgbaar zijn, is het nu mogelijk empirische gegevens in deze analyse te gebruiken. Deze aanpak bouwt voort op eerder onderzoek op basis van de genoemde onderzoeken naar voorkeuren van consumenten en stelt vragen aan de orde met betrekking tot het hiaat tussen waarde en actie. De centrale onderzoeksvraag van dit proefschrift is:

Hoe heeft de automobiellindustrie de ontwikkeling en commercialisering van elektrische voertuigen benaderd?

Om deze vraag te beantwoorden gebruikt dit proefschrift een aantal deelvragen die ieder een enkel hoofdstuk in dit document beslaan. Deze individuele onderzoeken zijn hieronder gedefinieerd, samen met hun respectievelijke gegevens en methodes.

Gegevens en methodes

Omdat de opkomst van een radicale innovatie zoals EV's vaak samenvalt met een constant veranderende markt en stijgende onzekerheid (in de literatuur een 'woelig tijdperk' genoemd), is het belangrijk dat analyses van deze situaties de meeste actuele en betrouwbare informatie gebruiken. In dit verband hebben afzonderlijke onderzoeken state-of-the-art dataverzamelmethodes gebruikt, waarbij gebruik is gemaakt van openbaar toegankelijke bronnen (die vaak de meeste actuele informatie bieden). Om de hoofdvraag van het proefschrift te beantwoorden was het nodig een brede set gegevens te verzamelen, waaronder informatie over allianties van fabrikanten, verkoopcijfers, openbare laadstations en prototype-/productiemodellen.

Dit proefschrift heeft zowel inferentiële als beschrijvende analysemethoden gebruikt, waaronder inhoudsanalyse (zowel kwalitatief als kwantitatief), lineaire regressie met behulp van de kleinste kwadratenmethode, t-tests en frequentieverdelingen. Vanwege de onzekerheid die een rol speelt bij de opkomst van een radicale innovatie is het denkbaar dat dit onderzoek niet alle relevante variabelen correct heeft vastgelegd, en de relaties tussen variabelen niet correct heeft vastgesteld. Daarom zijn statistische testen aangevuld met beschrijvende analysemethoden die identificeren waar de aangetroffen patronen (relaties tussen variabelen) niet standhielden, en die andere mogelijk relevante factoren en relaties aangaven. Tabel 1 geeft een globaal overzicht van de onderzoeksvraag, gegevens en analyse van ieder hoofdstuk

van het proefschrift. Een meer gedetailleerde beschrijving van de gegevens en analysemethode die zijn gebruikt, kunnen worden gevonden in de betreffende hoofdstukken.

Tabel 1: Overzicht van onderzoeksvraag, gegevens en methodes op hoofdstuk van het proefschrift.

Hoofdstuk	Onderzoeksvraag	Gegevens	Methodes
2	<i>Hoe zijn autofabrikanten te werk gegaan bij het vergaren van kennis over uiteenlopende sectoren om EV's commercieel te produceren?</i>	Allianties tussen autofabrikanten	T-test Binomiale analyse Beschrijvende analyses Inhoudsanalyse
3	<i>Hoe hebben gevestigde automerken de ontwikkeling van EV's benaderd in vergelijking met voertuigen die andere alternatieve brandstoffen gebruiken?</i>	Prototypes en productiemodellen van voertuigen met alternatieve brandstoffen	Beschrijvende analyses
4	<i>In welke mate hebben gevestigde fabrikanten en startups een verscheidenheid aan EV-types ontwikkeld op basis van criteria met betrekking tot formaat en prestaties?</i>	Prototypes en productiemodellen van elektrische voertuigen	Beschrijvende analyses
5	<i>In welke mate bieden financiële stimulansen en sociaaleconomische factoren een verklaring voor landelijke acceptatiepercentages van EV's?</i>	Acceptatiepercentages EV financiële stimulans inkomen, brandstof, etc.	Lineaire regressie Beschrijvende analyses
6	<i>Wat waren de belangrijke factoren die het initiële draagvlak voor EV's bij wagenparkbeheerders hebben beïnvloed?</i>	Interviews met wagenparkbeheerders	Inhoudsanalyse Beschrijvende analyses

Resultaten

In tegenstelling tot eerdere onderzoeken concludeert **Hoofdstuk 2** dat automerken een groot percentage (44%) aan allianties zijn aangegaan tijdens voorbereidende en vroege commercialiseringsfasen. Net als bij andere onderzoeken blijkt dat gevestigde fabrikanten een groter aantal allianties is aangegaan dan startups (twee keer zoveel), waardoor zij concurrentievoordeel hebben en de hogere waarde van hun beschikbaarheid van resources wordt benadrukt. Fabrikanten vertonen duidelijk patronen op het gebied van allianties binnen kennisgebieden zoals accu's en elektrische motoren, waarbij de voorkeur wordt gegeven aan onderzoekende samenwerkingsverbanden op het gebied van expertise waar ze graag kerncompetenties zouden willen hebben. Het grote aantal uitvoerende allianties die door fabrikanten werden gevormd geven echter aan dat zij samenwerkingsverbanden hebben ontwikkeld met zowel commercialisering als het vergaren van kennis tot doel. Met deze aanpak kunnen fabrikanten uitvoerende allianties gebruiken om EV's snel op de markt te

brengen en tegelijkertijd te investeren in gezamenlijke onderzoeken om intern de noodzakelijke expertise tot stand te brengen, zodat ze de volgende generatie auto's zelf kunnen creëren.

Resultaten van **Hoofdstuk 3** tonen dat tijdens de periode tussen 1991 en 2011 het aantal AFV's dat door autofabrikanten werd ontwikkeld ieder jaar vervijfvoudigd is en qua technische verscheidenheid verdubbeld is (gemeten naar brandstoftype dat gebruikt wordt in aandrijvingsmechanismes, zoals waterstof, elektriciteit en ethanol). In de vroege jaren 90 hebben bedrijven zich bijvoorbeeld primair gericht op het maken van voertuigen die op elektriciteit of waterstof reden; in de jaren tot 2010 ontwikkelden ze *ook* AFV's die ethanol, aardgas of een combinatie van alternatieve brandstoffen gebruikten. Dit suggereert dat autofabrikanten niet weten welke aandrijving in de toekomst succes zal hebben en dat ze klaar willen zijn voor alle mogelijkheden. Als gevolg hiervan lijkt het erop alsof de automobielenindustrie steeds meer twijfelt en turbulentie kent, vergelijkbaar met de situatie tijdens de overgangsfase die bekend staat als het 'woelige tijdperk' van de technologische cyclus. Mogelijk is dus een technologische overgang ingezet die leidt tot de opkomst van een nieuw dominant ontwerp voor auto's. Sinds 2007 zijn EV's en HEV's opgekomen als de meest veelvoorkomende AFV-modellen. Dit betekent dat er een stijgende impuls is voor deze aandrijvingsmechanismes, wat zich zou kunnen vertalen in een plaats als koploper waarbij andere AFV-ontwerpen achteraan in de rij mogen aansluiten.

Voortbouwend op de eerdere hoofdstukken constateren de resultaten van **Hoofdstuk 4** dat de EV-sector verschillende andere kenmerken vertoont die kenmerkend zijn voor een overgangsperiode, zoals een stijgend aantal bedrijven dat toetreedt, meer technologische verscheidenheid (op basis van accu-oplossingen) en nichemarkten die worden onderzocht. Gedurende de jaren 90 werden prototypes en productiemodellen van EV's voornamelijk ontwikkeld door grote gevestigde fabrikanten zoals Toyota, Volkswagen en General Motors. Vanaf circa 2004 kwam er een einde aan deze trend door startups die de meerderheid van de nieuwe EV-modellen gingen bouwen (voornamelijk prototypes). Bedrijven spendeerden een toenemende hoeveelheid resources aan het ontwikkelen van EV-technologie terwijl het aantal bedrijven dat een prototype of productiemodel aan het publiek presenteerden toenam van 1 in 2003 tot 76 in 2011. Technologische verscheidenheid heeft ook een verschuiving meegemaakt in de periode na 2004, toen lithium-kathoden in grote mate op nikkel gebaseerde configuraties in EV-accu's gingen vervangen. Ten slotte maakten de voertuigen zelf een verandering door toen bedrijven zich gingen richten op nichemarkten door de ontwikkeling van voertuigen met lage snelheden (topsnelheid van circa 25 mph), voertuigen met drie wielen, sportauto's en zeer kleine auto's zoals de Smart Fortwo. Wat betreft deze laatste verandering hebben gevestigde fabrikanten en startups de EV-markt op twee verschillende manieren benaderd. Gevestigde fabrikanten hebben voornamelijk EV's ontwikkeld waarbij formaat en prestaties (topsnelheid) overeenkwamen met kenmerken van gangbare ICEV's; voorbeelden zijn de Nissan Leaf en de Tesla Model S. Aan de andere kant hebben startups EV's ontwikkeld in alle segmenten, maar waren zij kenmerkend anders dan gevestigde bedrijven wat betreft de manier waarop zij nichemarkten onderzoeken. Denk ook aan het gebrek aan succes dat startups hebben gehad in het verkopen van EV's, met uitzondering van Tesla. In 2011 waren bijna alle verkochte EV's gebouwd door gevestigde fabrikanten en leken ze wat formaat en topsnelheid betreft op conventionele ICEV's.

Hoofdstuk 5 beschrijft hoe financiële stimulansen, het aantal laadstations (gecorrigeerd voor de bevolking) en de aanwezigheid van een lokale productieorganisatie voor EV's een positieve en significante invloed hebben bij het inschatten van draagvlak voor EV's, tenminste voor de landen in ons onderzoek. Van deze variabelen waren kenmerken van de

infrastructuur met laadstations de beste voorspeller van het marktaandeel van EV's in een land. Zelfs met een sterke correlatie was er echter een hoge mate van heterogeniteit in de nationale acceptatie van EV's, het niveau aan financiële stimulans of de kenmerken van de laadinfrastructuur. Beschrijvende analyses geven aan dat landspecifieke factoren zoals aanbestedingsplannen van de overheid of commerciële bedrijfsmodellen mogelijk een invloed hebben gehad op deze relatie en het acceptatiepercentage van een land dramatisch hebben beïnvloed. In 2012 heeft bijvoorbeeld de regering van Estland besloten 500 Mitsubishi MiEV's aan te kopen (na een totaal van slechts 55 aankopen in Estland in 2011) en een uitgebreid netwerk van snelle laadpunten te installeren. Deze plotselinge toename van EV's en de bijbehorende infrastructuur heeft ertoe geleid dat Estland het op één na hoogste marktaandeel heeft van alle landen in ons onderzoek (Estland uit ons model verwijderen heeft de resultaten niet significant gewijzigd). Een dergelijke grote invloed met betrekking tot acceptatie van EV's door aanbestedingen van de overheid is in andere landen niet voorgekomen. Wat betreft de invloed van fabrikanten bij het draagvlak voor EV's hebben verschillende bedrijven, zoals Ford en Toyota, het hoogste aantal verkopen gehad in het land waar hun productiefaciliteiten zich bevinden, wat aangeeft dat er een complexe relatie is tussen consumenten, automerken en de landelijke houding ten opzichte van elektrische auto's. Samenvattend werd ontdekt dat EV-gerelateerde factoren zoals de infrastructuur van oplaadpunten, financiële stimulansen en de aanwezigheid van productiefaciliteiten voor EV's betrouwbare voorspellers zijn voor het marktaandeel, terwijl meer brede sociaal-demografische variabelen zoals inkomen, opleidingsniveau en milieubewustzijn geen significante invloed hadden.

Resultaten van **Hoofdstuk 6** hebben vastgesteld dat tijdens de initiële beslissing van wagenparkbeheerders om een EV wel of niet aan te kopen, ze werden beïnvloed door een verscheidenheid aan factoren, waaronder de wens om nieuwe technieken te testen, lagere milieubelasting, de beschikbaarheid van overheidssubsidies ende mate van interesse in het verbeteren van het publieke imago van de organisatie. Hiervan was het testen van nieuwe technieken de sterkste en belangrijkste factor in het motiveren van organisaties om te kiezen voor EV's. Ook waren er belangrijke redenen die voortkwamen uit de achtergrond van een (overheids- of commerciële) organisatie; de beslissingen van verschillende overheidsinstanties werd beïnvloed door beperkende wetgeving, terwijl commerciële bedrijven potentiële financiële voordelen zagen in hun keuze om een van de eersten te zijn en dit zwaar lieten meewegen in hun beslissing om voor EV's te kiezen. Wanneer ze besloten om het aantal EV's wel of niet uit te breiden, maakten wagenparkbeheerders hun keuze met name op basis van factoren die voortkwamen uit hun bedrijfsbelang, zoals het voordeel een van de eersten te zijn, gespecialiseerde operationele capaciteiten of een aantrekkelijk bedrijfsmodel. Een brede conclusie die uit dit onderzoek kan worden getrokken, is dat de eerste golf EV's over het algemeen een verlies betekende voor organisaties. Sommige wagenparkbeheerders konden deze kosten verantwoorden door middel van andere voordelen dan financiële voordelen, met name vanwege de kans om nieuwe technieken te testen wat tot acceptatie van EV's zou leiden. Organisaties die later besloten hun wagenpark van EV's uit te breiden, deden dit vanwege organisatorische redenen.

Conclusies

Conclusies die uit deze onderzoeken worden getrokken, stellen de onderzoeksvraag van dit proefschrift aan de orde: hoe is de automobieliindustrie aan de slag gegaan met het ontwikkelen en commercialiseren van elektrische voertuigen? Resultaten tonen dat factoren die hieraan hebben bijgedragen bijvoorbeeld de manier is waarop fabrikanten relevante

expertise hebben verzameld, de types auto's die ze hebben ontwikkeld, de dominantie van gevestigde automerken en de locatie waar EV's commercieel geïntroduceerd zijn.

Aangezien het verwerven van nieuwe expertise van cruciaal belang is voor radicale innovaties en bedrijven steeds vaker samenwerken met externe organisaties die deze kennis reeds in huis hebben, is het vormen van allianties zeer belangrijk voor de ontwikkeling van EV's. Gevestigde autofabrikanten zijn meer allianties op het gebied van EV's aangegaan dan startups, een strategie die de bedrijven in staat stelt intern kritieke expertise op te bouwen door middel van onderzoekende samenwerkingsverbanden. Gevestigde bedrijven hebben zo een positie ingenomen om EV's te ontwikkelen terwijl ze ook dicht bij hun bestaande bedrijfsmodel en ervaring blijven.

Naast een dramatische stijging van het aantal prototypes van EV's hebben autofabrikanten ook een toenemend aantal voertuigen ontwikkeld die op twee soorten brandstof rijden, zoals benzine of diesel met een alternatieve brandstof als elektriciteit, CNG of ethanol. Dit suggereert dat bedrijven zich in toenemende mate bezighouden met de ontwikkeling van AFV's, in plaats van vast te houden aan een vaste koers om een meer radicale innovatie van aandrijvingsmechanismes te commercialiseren. Dit betekent dat, terwijl autofabrikanten resources aanwenden voor de marktintroductie van EV's en FCV's, deze inspanningen worden gematigd doordat ze zich tegelijkertijd richten op het ontwikkelen van AFV's die meer lijken op het bestaande ontwerp van ICEV's, bijvoorbeeld HEV's en voertuigen op twee soorten brandstof.

Startups hebben een breed scala aan onconventionele EV's ontwikkeld, zoals voertuigen met 3 wielen, voertuigen met lage snelheden en zeer kleine auto's. Daarentegen hebben gevestigde firma's hun ontwerpen van EV's gebaseerd op de verwachtingen betreffende formaat en prestaties van ICEV's. Tot op heden zijn gevestigde fabrikanten verantwoordelijk voor de overgrote meerderheid verkochte EV's. Aldus blijft de opkomende EV-branche sterk verbonden met het bestaande paradigma ten opzichte van deelnemende fabrikanten en voertuigkenmerken zoals formaat en prestaties.

Hoewel autofabrikanten daarnaast early adopters van EV's in verschillende landen proberen te bereiken, hebben ze zich voornamelijk geconcentreerd op hun eigen landen en daar de meeste successen geboekt, zoals Toyota in Japan, Ford in de V.S., en Renault in Frankrijk. Hoewel dit waarschijnlijk de gemakkelijkste verkopen zijn, geeft dit ook aan dat bedrijven een beperkte uitrol van EV's wereldwijd nastreven. Als gevolg hiervan zullen de distributiekanaalen, die momenteel af lijken te nemen, waarschijnlijk leiden tot lagere acceptatie van EV's, in plaats van een situatie waarbij fabrikanten hun EV's breed beschikbaar maken over de hele wereld.

Deze conclusies laten zien dat, hoewel de automobieliindustrie een strategie heeft gevolgd die mogelijkheden van EV's heeft onderzocht, bedrijven over het algemeen bij hun relatieve ervaringen en bedrijfsmodellen gebleven zijn. Dit weerspiegelt een geleidelijke en weloverwogen aanpak om EV's te ontwikkelen in plaats van een meer agressieve houding die zou worden aangenomen door startups die enkel elektrische auto's produceren. Op basis van bovenstaande bevindingen is de primaire conclusie van dit proefschrift dat een overgang naar EV's langzaam zal zijn, als deze al plaatsvindt.

Aanbevelingen betreffende beleid

Vanuit maatschappelijk oogpunt zou dit proefschrift niet moeten worden gezien als het bejubelen van EV's als toekomst voor duurzame automobilitéit maar eerder als voorzichtig

optimisme vanwege de mogelijkheden van de innovatie. De snelle toename van oplaadpunten van de afgelopen tijd, beschikbare productiemodellen en verkoopcijfers geven aan dat EV's een impuls aan de markt geven. Gevestigde autofabrikanten zullen echter mogelijk aarzelen om zwaar te investeren in de ontwikkeling en introductie van EV's, met name in vergelijking met startups die enkel elektrische auto's verkopen. Als het beleidsdoel daarom is om een technologische overgang te bespoedigen, zijn er waarschijnlijk extra inspanningen nodig, waaronder strengere richtlijnen betreffende uitstoot, het uitbreiden van oplaadpunten, het aanbieden van financiële stimulansen en het toepassen van voorlichtingscampagnes om invloed uit te oefenen op de ideeën van consumenten over EV's.

Hoewel onderzoek naar en ontwikkeling van EV's moet blijven doorgaan, worden beleidsmakers aangeraden deze techniek niet als de onvermijdelijke toekomst van duurzame automobilité te beschouwen. Ook al kunnen radicale technieken zoals FCV's en EV's de meest dramatische verbeteringen bieden als het gaat om individuele uitstoot van auto's, ook incrementele vooruitgang biedt een kans voor substantiële opbrengsten. Hybride mogelijkheden, lichtgewicht materialen en verbeteringen van technologische efficiëntie die worden gebruikt bij een groot aantal voertuigen zouden kunnen leiden tot hogere dalingen van emissies dan geringe acceptatie van EV's of FCV's. In plaats van zich te richten op één techniek zouden beleidsmakers resources moeten wijden aan het ontwikkelen van een gevarieerde set aan mogelijke aandrijvingsmechanismes. Gesuggereerd beleid is bijvoorbeeld brede regelgeving op het gebied van vermindering van uitstoot, financiële stimulansen voor consumenten gericht op het verminderen van vervuiling door auto's en subsidies voor R&D voor interessante innovaties.

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