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The competitive environment of electric vehicles: An analysis of prototype and production models

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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.

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[1]) is a prominent contender. EVs are not a new innovation,

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

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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-CO_2 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.

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 CO_2 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) CO_2 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.

2. Theory

Within technological innovation literature, the product life 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 product life 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 *product life 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.

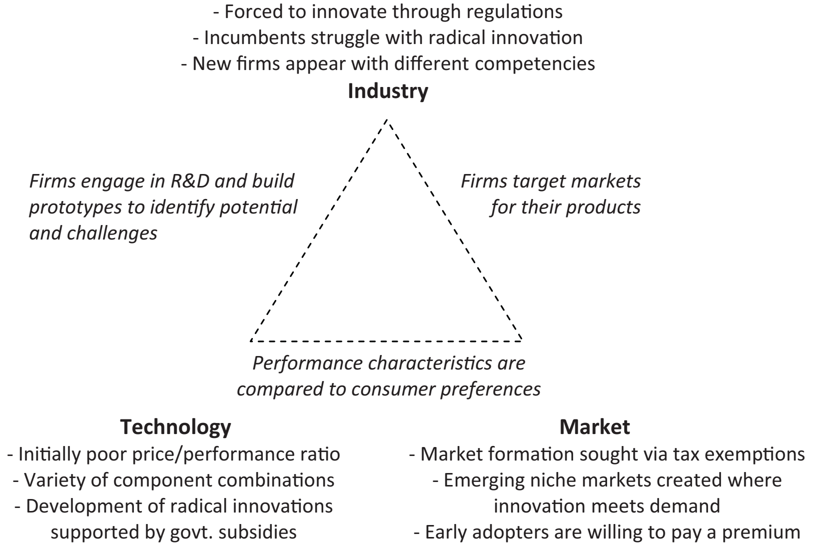

Fig. 1. Research framework for eco-innovations during an era of ferment.

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 product life 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). Fig. 1 depicts this relationship in the product life 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 relatively 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.

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

Table 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%

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 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.

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-do-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 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 product life 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, multi-purpose (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 2 and 3. In addition, the categories of LSVs and 3-wheelers were also included because of their prevalence among EV models.

Table 2
Vehicle classification scheme (SMMT, 2009).

	Engine size	Vehicle length	ICE example	EV example
Mini	~1.0 cc	<3050 mm	Smart ForTwo	Tezzari Zero
Small	~1.0–1.4 cc	<3745 mm	VW Polo	BMW Mini E
Compact	~1.3–2.0 cc	<4230 mm	VW Golf	Volvo C30 EV
Upper-medium	~1.6–2.8 cc	<4470 mm	VW Passat	Nissan Leaf
Executive	~2.0–3.5 cc	<4800 mm	Daimler CL600	BYD Auto e6
Luxury	>3.5 cc	N/A	Cadillac CTS	Rolls Royce 102 EX

Table 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	4×4 off road	Ford Escape	Toyota Rav4 EV
LCV	≤3.5 tons	Jeep Wrangler	E-wolf Omega 1.4
HCV	>3.5 tons	Freightliner Cascadia	Balqon Nautilus E20
Bus	Can carry >10 persons	Champion Defender	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).

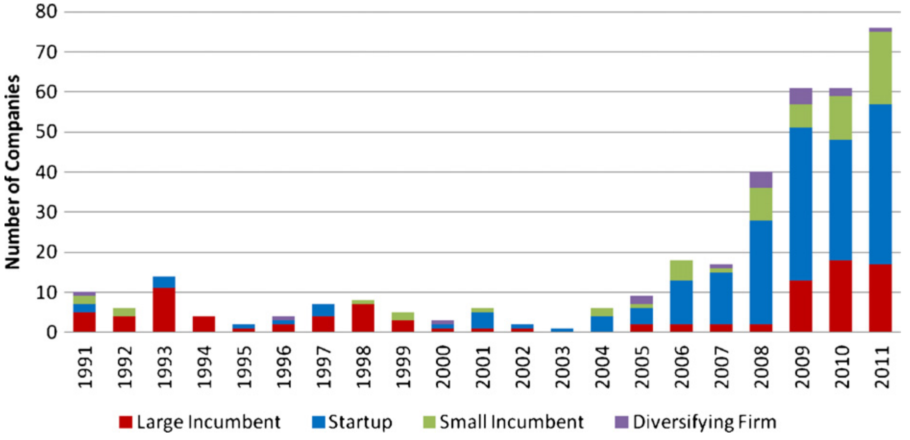

Fig. 2. Companies producing electric vehicles.

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. Fig. 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. Fig. 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 product life 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).

Fig. 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

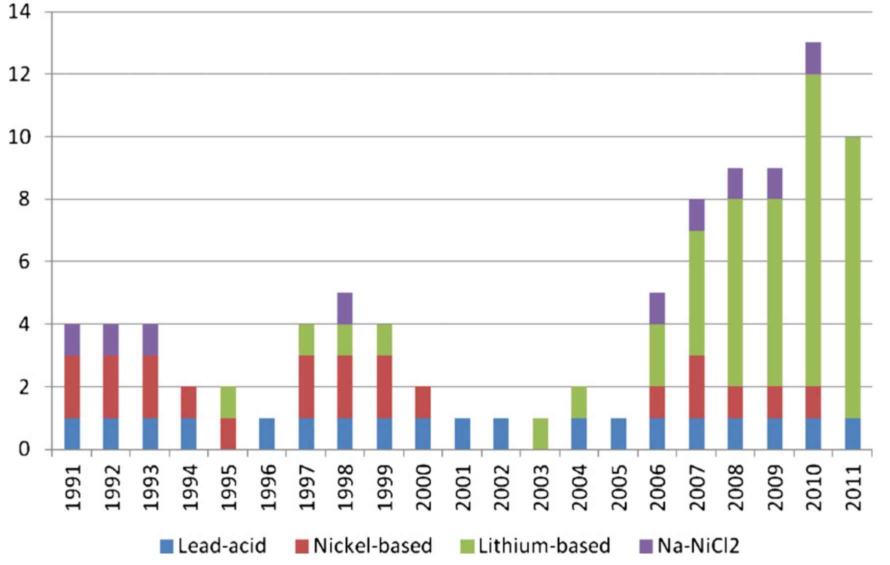

Fig. 3. Unique battery chemistries in electric vehicle models.

zebra batteries seems to be largely tied to one company (MES-DEA later known as FZ Sonick) which produce 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.

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 shows a breakdown of the lithium-ion battery chemistries that were used in EV models from the data set. 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

Table 4
Lithium-ion battery chemistries.

Cathode	Anode	Electrolyte
$LiCoO_2$	LiC_6	Organic solvent
$LiFeMnPO_4$	LiC_6	Organic solvent
$LiFePO_4$	LiC_6	Organic solvent
$LiMn_2CoO_4$	LiC_6	Organic solvent
$LiMn_2O_4$	LiC_6	Organic solvent
$LiMn_2O_4$	LiC_6	Poly. composite
$LiMn_2O_4$	$Li_4Ti_5O_{12}$	Organic solvent
$Li(NiCoAl)O_2$	LiC_6	Organic solvent
$Li(NiMnCo)O_2$	LiC_6	Organic solvent
$Li(NiMnCo)O_2$	LiC_6	Polymer composite
$Li_3V_2(PO_4)^3$	LiC_6	Organic solvent
$Li_3V_2(PO_4)^3$	LiC_6	Polymer composite

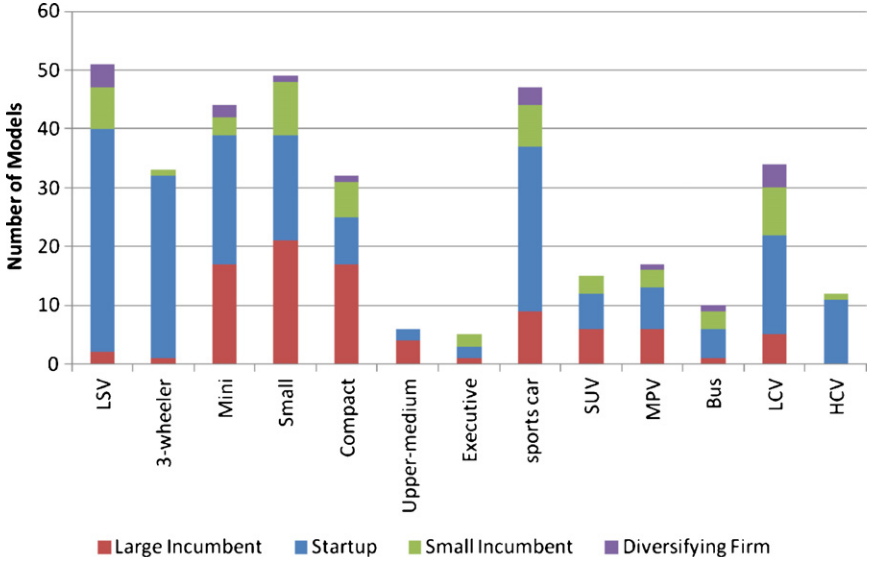

Fig. 4. Electric vehicle classification by manufacturer type.

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 will focus on EV models from 2004 to 2011.

Fig. 4 breaks 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

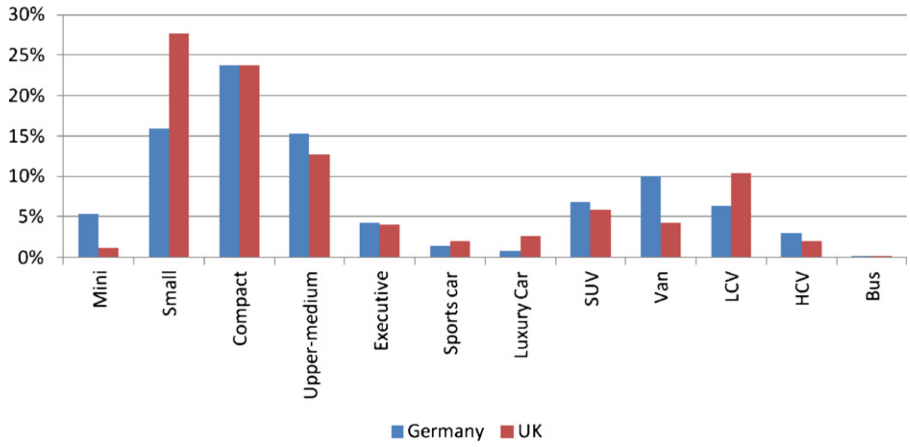

Fig. 5. 2008 German and United Kingdom new car registrations.

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.

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 Fig. 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.

Fig. 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 Figs. 4 and 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 Fig. 4 (LSV, sports cars, 3-wheelers and mini) accounted for 49% of all EV models produced from 2004 to 2011. In Fig. 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

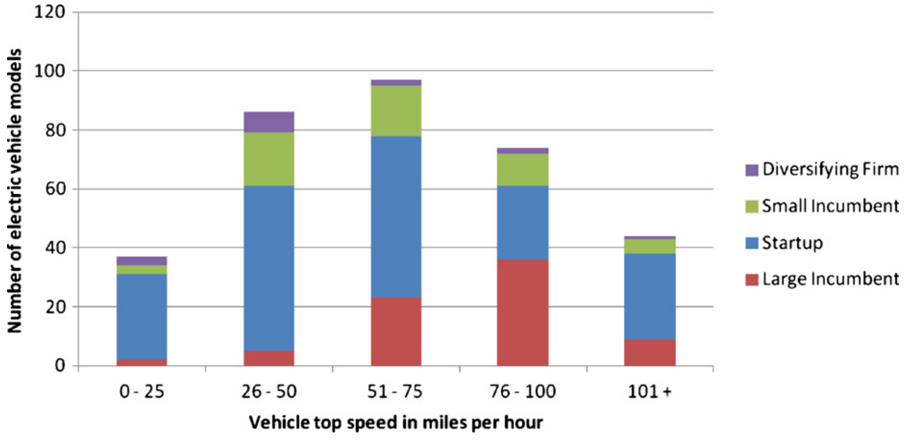

Fig. 6. Electric vehicles by top speed and manufacturer type.

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.

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.

Fig. 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 Fig. 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 vehicles 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.

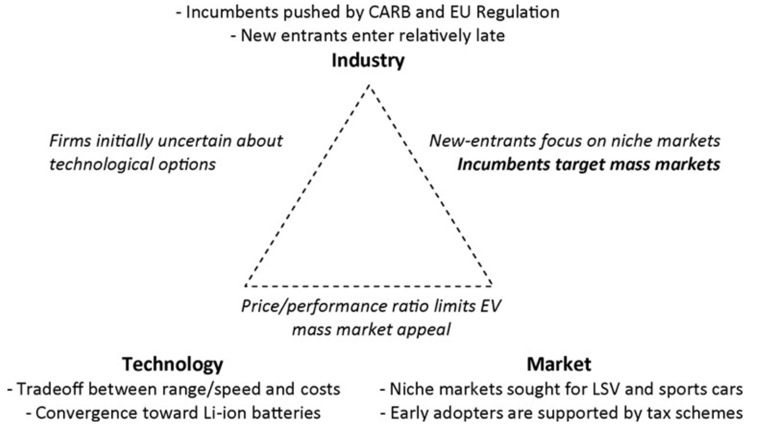

Fig. 7. Conclusions represented in the analytical framework.

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. Fig. 7 identifies these and other results relative to the analytical framework outlined in Section 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.

Acknowledgement

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Appendix A. 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

Appendix A (*Continued*)

UK	United Kingdom
US	United States
V	Vanadium
ZEV	Zero emissions vehicle

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