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La Follette School of Public Affairs

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Working Paper Series

La Follette School Working Paper No. 2015-002

<http://www.lafollette.wisc.edu/publications/workingpapers>

Using Patents and Prototypes as Preliminary Indicators of Technology-Forcing Policies: Lessons from California's Zero Emission Vehicle Regulations

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February 2015



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**Using patents and prototypes as preliminary indicators of technology-forcing policies:
Lessons from California's Zero Emission Vehicle regulations**

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Abstract

Technology-forcing policies are one of several measures that governments have at their disposal in order address market failures arising from knowledge spillover and pollution externalities. However due to uncertainty and information asymmetry, pre-commercial evaluation of these policies can be difficult, especially for radically novel technologies. We use a case study of California's Zero-Emissions Vehicle (ZEV) regulations and their impact on electric vehicle technology development by the 21 largest auto manufacturers 1991-2013 to determine whether patents and prototypes are valid preliminary indicators to evaluate the subsequent effectiveness of technology-forcing policies. In order to better understand automaker R&D activity, it was necessary to include a global perspective. The results show that patents, when embedded within a global industrial perspective, can be used to analyze technology-forcing policies, which provides a helpful tool for policy makers gauging the ex-ante effectiveness of these types of regulations.

Keywords: Public policy, technology adoption, electric vehicles, eco-innovation

1. Introduction

Technology-forcing policies are one of several regulatory measures that governments have at their disposal in order to advance innovation (Ashford et al., 1985; Rennings, 2000). These regulations mandate performance levels above current technological capabilities or the adoption of specific innovations that are not yet fully developed (Jaffe et al., 2002; Lee et al., 2010). They “can be used to encourage all varieties of technological innovation as well as diffusion for both product and process change” (Ashford et al., 1985 p.463). The rationale for their use is when, “. . . a technological fix of the problem can only be brought about by applying regulatory pressure on firms” (Gerard and Lave, 2007, p. 3). Market failures arising from knowledge spillover and pollution externalities provide justifications for policymakers to use this type of regulation (Rennings, 2000). One result of knowledge spillover is that companies engage in reduced levels of early-stage innovation when they are not fully compensated for the benefits of their efforts. (Jaffe et al., 2005). Technology-forcing policies can be used to overcome this barrier while also helping correct for underpriced environmental externalities if the innovation being pushed creates fewer pollution externalities than the alternative.

The automotive sector in particular has seen a great deal of environmental innovation based on technology-forcing emissions legislation (Gerard and Lave, 2005; Gerard and Lave, 2007). As a case in point, US Corporate Average Fuel Economy (CAFE) standards and EU vehicle emissions regulations have helped drive the auto industry toward the use of more efficient combustion engines (EPA, 2010; European Commission, 2009; Nemet, 2014). Similarly, the 1970 US Clean Air Act led to the development of the catalytic converter in 1975 and three-way catalyst in 1981, reducing vehicle emissions (Hackett, 1995).

Researchers have engaged in extensive *ex post* analysis of the costs and merits of technology-forcing legislation relative to other measures e.g., subsidies or tax credits¹ (Freeman and Haveman, 1972; Ashford et al., 1985; Jaffe et al., 2003), but these studies provide limited guidance for decision makers who are crafting policy. The primary issue is one of uncertainty; because technology-forcing policies address innovations whose future dynamics are inherently unknowable they are associated with high levels of ambiguity for policymakers. Regulators do not know what levels of technological improvements are likely without a policy or what levels are feasible with such legislation. Thus, regulation innovation targets risk being either too weak to lead to meaningful change, or too ambitious to be achievable (Freeman and Haveman, 1972). Given the technical information required, technology-forcing legislation entails constant interaction between regulators and firms to determine investment; levels of technological progress; and how those two factors relate to established goals (Hackett, 1995). Policy stringency may have to be adjusted, as it was for California’s ZEV regulations, depending how the target technology is developing (Collantes and Sperling, 2008).

Increased levels of uncertainty are specifically associated with technology-forcing policies when they influence pre-commercial development. Once an innovation is available on the market regulators can

¹ This article is not meant to compare the relative merits of innovation policies, but in general, researchers have found technology-forcing policies to have a relatively higher cost than other measures such as subsidies or tax credits (Jaffe et al., 2003).

look at sales figures to help adjust policy, but before commercialization there are limited ways for policymakers to gauge the progress of a technology. This issue is compounded by information asymmetries between regulators and firms, specifically when innovations have lengthy development cycles. For example, in order to reduce the cost of a technology-forcing policy firms may downplay progress or exaggerate the level of resources necessary to reach a stated goal (Gerard and Lave, 2005). As a result, regulators often do not have a good understanding of how well companies are progressing toward the policy's targets. This leaves the period of time while an innovation is being developed where policymakers have limited means to analyze the effectiveness of a technology-forcing regulation.

An additional limitation in the understanding of technology-forcing policies is that studies have traditionally confined analyses to individual countries (Freeman and Haveman, 1972; Ashford et al., 1985; Jaffe et al., 2003). Consequently, they do not incorporate important global market dynamics, such as R&D by foreign firms. This can become especially problematic when regulatory impacts are determined by firm size and companies are involved in markets outside the policy reach. Thus, including global market dynamics should lead to a better understanding of the general impact of technology-forcing policies.

This study is meant to address the above literature gaps and policy problems in two ways. First, it will determine whether pre-commercial development, in the form of patents and prototypes, might provide useful preliminary measures of the effectiveness of technology-forcing policies. Second, it will analyze how these types of regulations influence firm R&D where companies have different approaches to innovation commercialization. Our paper accomplishes these two goals by testing the following hypotheses:

- Technology-forcing policies will result in firms increasing the number of prototypes that they develop and patents that they receive.
- Firms that pursue mass market commercialization of an innovation will have higher levels of patents and prototypes than companies seeking to meet regulation requirements, which in turn will have higher R&D levels than those refraining from market introduction.

To test this hypothesis, we analyze the impact of ZEV regulations on the development and market introduction of electric vehicles (EVs).

1.1. Research case

The effect of ZEV regulations on EV commercialization is a good case to analyze indicators of technology-forcing policies for three reasons. First through David Vogel's "California effect" (1995) ZEV regulations, which govern about 30% of the US market (Mui and Baum, 2010), have the potential to influence auto maker activity around the world. The California effect has shown how environmental policies in large markets can drive firms to meet more stringent regulatory requirements. For example, California's vehicle emissions requirements have been an important contributing factor to increases in US national emissions standards. (Vogel, 1995). Second, auto makers have chosen several different approaches to the introduction of commercial EVs with some companies taking a mass market tack; others seeking to only meet the regulatory minimum; and a third group eschewing commercialization all together. And

third, the electric vehicle case offers an opportunity to analyze the relationship of patents and prototypes to a technology-forcing policy because auto makers use both innovation indicators when developing alternative-fuel vehicles (Oltra and St. Jean, 2009; Sierzchula et al., 2012a).

In addition, this study provides the prospect of influencing the evolution of ZEV policies. The electric vehicle industry offers extensive historical data while EV development and early adoption is still in a formative period. Thus, analysis provided by this study could be of particular relevance to regulators that are updating ZEV regulations.

1.2. ZEV Policy Origins

The California Air Resources Board's (CARB) 1990 ZEV regulations were designed to encourage development and diffusion of new powertrain technologies (Bedsworth and Taylor, 2007). They forced auto makers to include a percentage of zero-emission vehicles, e.g. fuel-cell electric vehicles (FCEVs) or EVs, in their annual sales to maintain access to section 177 state auto markets;² otherwise, the firms would face financial penalties³ (CA DMV, 2014; Wesseling et al., 2014). This legislation led automakers to introduce several electric vehicles in the mid to late 1990s (Sierzchula et al., 2012a). However, based on a 2002 legal challenge from the auto industry, ZEV regulations were weakened as they were eventually determined to mandate compliance based on options that were unrealistic (Collantes and Sperling, 2008). After several years of weak incentives, the policy's stringency increased for 2009 model year vehicles. This change resulted in auto makers having to produce ZEV credits in order to meet the policy's minimum requirements. These can be acquired through sales of EVs/FCEVs or purchased from other manufacturers. Sales of ZEVs prior to 2009 are included in auto manufacturer credits. A timeline of important ZEV regulation events is available in Figure 1, while a more complete summary can be found in Wesseling et al. (2014).

² This term specifically refers the authorizing section of the clean air act, and covers states that have chosen to adopt California's emissions standards instead of federal requirements, including: Connecticut, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont, Washington, which represent approximately 30% of the US auto market (Mui and Baum, 2010).

³ Each section 177 state determines its own penalty level for noncompliance. For instance, California penalizes auto makers \$5,000 for each ZEV credit not produced.

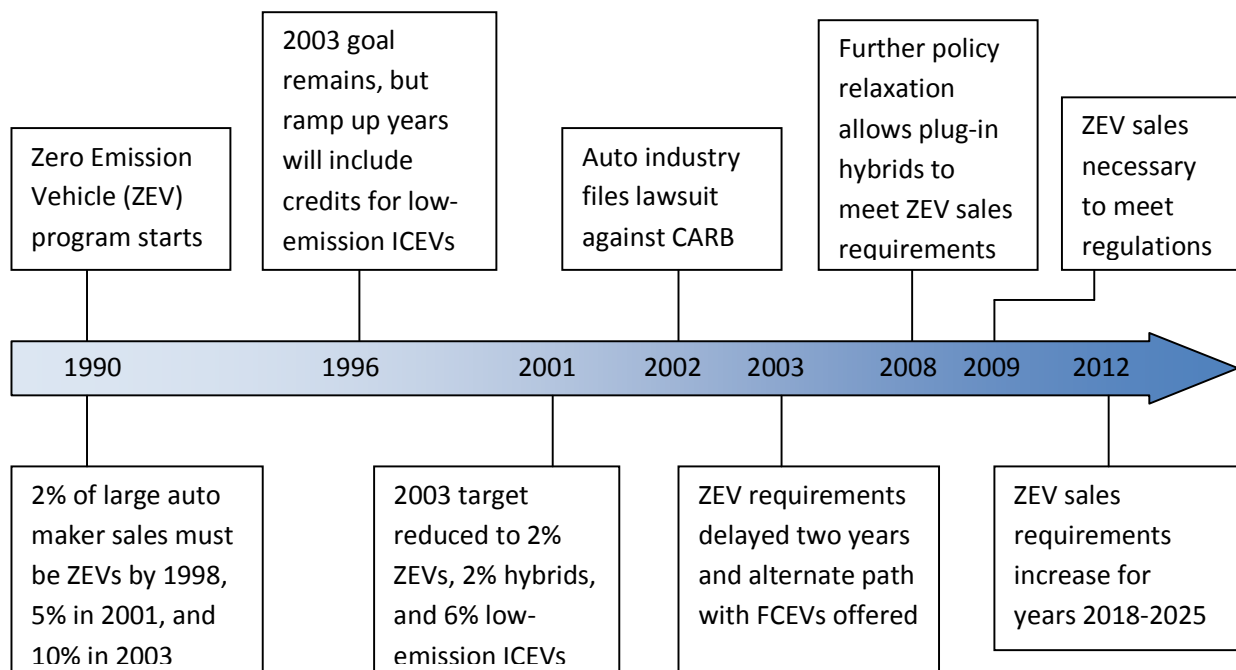


Figure 1. Zero-Emission Vehicle program timeline.

Due to changes in ZEV regulations identified in Figure 1, automakers have only recently actually had to produce ZEV credits. From 2009-2014, Large Volume Manufacturers (LVMs) have needed to acquire ZEV credits equal to 0.79% of their annual sales, increasing to 3% in 2015, and 22% in 2025 (CARB, 2014a; CARB, 2014b). Credits are determined based on the type of fuel a vehicle uses, emissions, zero-emission driving range, and presence of advanced components. For example, if Tesla sold a Model S in 2012, it would receive seven ZEV credits; if Toyota sold a Prius it would receive 0.35 ZEV credits. There is also a phase-in multiplier that increases the ZEV credits earned for a vehicle sold prior to 2011. It should be noted that the ZEV requirements themselves are much more detailed and include multiple types of vehicles e.g., plug-in hybrids and neighborhood electric vehicles, than what is noted in this section. For the complete regulations, please see the CARB website (CARB, 2014a; CARB, 2014b).

ZEV regulations make a sharp distinction between LVMs that have California annual sales greater than 60,000, Intermediate Volume Manufacturers (IVMs) that have annual California sales between 4,501 and 60,000, and other car makers with sales less than 4,501. LVM firms (GM, Ford, Nissan, Toyota, Chrysler, Honda, and Mazda) have been subject to the most stringent ZEV requirements, while IVMs can meet their requirements until 2017 through selling hybrid electric vehicles (HEVs) e.g., Toyota Prius and thereafter by selling plug-in HEVs e.g., Chevy Volt (CARB, 2014a; CARB, 2014b).

While in the 1990s auto makers introduced a small number of lease-only EVs, in the late 2000s such automobiles were made available for purchase. However, there was a sharp distinction between the manufacturers that apparently intended to sell EVs on a mass scale and those that only wanted to fulfill ZEV regulations. For example, regarding sales of their 500e Fiat Chrysler’s CEO said, “I’ll sell the limit of what I’m required to sell and not one more” (Brookings, 2014). This indicates that at least Fiat is selling

just enough EVs to maintain access to the California auto market. Other auto makers, notably Nissan, have taken a mass market approach to EV commercialization.

1.3. Electric vehicle policy and development history since 1990

The introduction of GM's electric concept vehicle *Impact* at the 1990 Los Angeles Auto Show and subsequent announcement that the automobile would be brought to production marked a shift in auto maker development of and government policies regarding EVs (Bedsworth and Taylor, 2007; Dijk et al., 2013). During the 1990s, countries around the world introduced a wide range of policies to stimulate EV development and adoption. In addition to California's ZEV regulations, European nations encouraged the introduction of EVs largely through public R&D programs and by funding 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 also issued an aggressive market expansion policy in 1991, followed by a series of pilot projects throughout the 1990s (JEVA, 2000).

Meanwhile, 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 (Sierzchula et al., 2012a). Only a few of these prototypes were ever introduced to the market as production models, notably GM's EV1 and Toyota's RAV4 EV. However by the early 2000s, manufacture of EVs had practically stopped due to factors such as: consumer uncertainty, high purchase price, limited driving range, low fuel costs, and little charging infrastructure (Dijk et al., 2013). Because of these issues, particularly high production costs, manufacturers determined that selling EVs was not a viable business model; pilot projects ended, supportive policies were severely watered down, and auto makers gradually retreated from the EV market (Patchell, 1999; Funk and Rabl, 1999; Dijk and Yarime, 2010).

In the late 2000s, 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. The wide-scale commercialization of the Nissan LEAF and Mitsubishi i-MiEV in 2009 along with the appearance of startup manufacturers such as Th!nk and Tesla indicated a level of momentum behind the most recent introduction of EVs. And while there is disagreement about their future success prospects (Wells and Nieuwenhuis, 2012; Dijk et al., 2013), EVs have reached a level of commercialization much greater than that found in the 1990s. However, a general conclusion about this recent market emergence is that any sort of broad EV diffusion will 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 some large auto makers now view some EV markets as a commercial opportunity instead of a regulatory requirement (Magnusson and Berggren, 2011).

2. Methods

In this section, we describe the data collection and analysis methods used to test our hypotheses. First, we identify the auto maker sample and the study timeframe. Then, we explain how we categorized auto makers according to their ZEV status and EV commercialization approach. Finally, we detail how data for

dependent variables (patents and prototypes) and independent variables were collected and also the model estimation used on the analysis.

2.1. Data

The data for our study consists of commercialized models, prototypes, and patents from the 21 largest auto manufacturers in the world between 1991 and 2013. This time-frame was selected because it captured auto maker behavior after ZEV regulations were implemented in 1990. Additional independent variables were used to control for other factors that may have influenced auto maker patent applications and prototype introductions.

2.1.1. Firm selection

The firms used in this study include the following auto manufacturers: BMW, Chrysler, Daimler, Dongfeng, FAW, Fiat, Ford, Geely, General Motors, Honda, Kia/Hyundai, Mazda, Mitsubishi, Nissan, PSA, Renault, SAIC, Suzuki, Tata, Toyota, and Volkswagen.⁴ These firms were selected because they are the biggest car makers in the world, accounting for 89% of global vehicle production in 2012 (OICA, 2014). Researchers have frequently used large auto manufacturers in patent and prototype studies of the auto industry (Oltra and St. Jean, 2009; Bakker et al., 2012; Sierzchula et al., 2012b; Wesseling et al., 2013). In addition, each of the auto makers in this sample introduced at least one EV prototype if not a commercial model, indicating a certain amount of firm-level commitment to developing the innovation.

2.1.2. Commercialized EVs

In order to test the hypotheses of this paper, it was necessary to differentiate between how auto manufacturers have been affected by ZEV regulations, and their various approaches to EV commercialization. For the first hypothesis, the important distinction is how ZEV regulations separate auto makers into the following groups – LVMs, IVMs, or companies for whom the policy is Not Applicable (N/A). Using California auto sales, ZEV categorization of auto makers in this study is identified in Table 1.

Table 1.

ZEV categorization of auto manufacturers

| LVMs | IVMs | N/A |
|----------|------------|-----------------|
| Chrysler | BMW | Dongfeng |
| Ford | Daimler | FAW |
| GM | Hyundai | Fiat |
| Honda | Mazda | Geely |
| Nissan | Mitsubishi | PSA |
| Toyota | Volkswagen | Renault SAIC |

⁴ Tesla was not included in this list because it has only been selling EVs since 2006, and represents a fundamentally different firm than the other incumbent auto makers. For example, Tesla had 1/8th of VW's patent total (the mass market auto manufacturer with the lowest number of patents).

Suzuki
Tata

We made four additional adjustments to auto maker ZEV status in our study due to merger or takeover. Daimler shifted from being an IVM to LVM from 1998-2007 because of its merger with Chrysler. After 2007, Daimler was again categorized as an IVM. Similarly, Fiat was labeled a LVM from 2011-2013 because of its merger to Chrysler. In our data, both Daimler/Chrysler and Fiat/Chrysler were considered separate firms throughout the study. There is precedence for this in the literature stemming from their being separate legal entities (Sarasini, 2014). Tata and Geely were designated IVMs after they purchased manufacturers with that status – Land Rover and Volvo respectively.

The second hypothesis requires determining auto maker EV commercialization strategy. To do this, we combined auto maker ZEV status from Table 1 along with the number of sales for each firm’s top-selling EV model and the number of countries where the automobile is available; the results are presented in Table 2.

Table 2.

Top EV model sales, national availability of the automobile, and auto maker ZEV status⁵

| Auto maker | EV model | # of units sold | # of countries available for purchase | ZEV status |
|-------------|-------------|-----------------|---------------------------------------|------------|
| Nissan | LEAF | ~140,000 | 35 | LVM |
| Mitsubishi | i-MiEV | 20,916 | 25 | IVM |
| Renault | Zoe | 12,631 | 10 | N/A |
| BMW | i3 | 11,676 | 14 | IVM |
| PSA | iOn/C-Zero | 11,084 | 19 | N/A |
| Daimler | ForTwo ED | 8,580 | 8 | IVM |
| Volkswagen | e-up | 6,037 | 11 | IVM |
| Hyundai/Kia | Soul EV | ~5,000 | 10 | IVM |
| Ford | Focus EV | 3,957 | 1 | LVM |
| Fiat | 500e | 3,748 | 1 | LVM |
| Toyota | RAV4 EV | 2,255 | 1 | LVM |
| GM | Spark EV | 1,434 | 2 | LVM |
| Honda | Fit EV | 1,007 | 1 | LVM |
| SAIC | E50 | 644 | 1 | N/A |
| Geely | Geely/Kandi | 304 | 1 | N/A |
| Dongfeng | - | - | - | N/A |
| FAW | - | - | - | N/A |
| Mazda | - | - | - | IVM |
| Suzuki | - | - | - | N/A |
| Tata | - | - | - | N/A |

If we consider auto manufacturers with national availability in more than 5 countries and sales above 5,000 units to be targeting a mass market audience, then most of the auto makers in the study sample

⁵ The sources for Table 2 are manufacturer websites and Insideevs (2014).

fall into one of three different approaches to EV commercialization: mass market, regulatory requirement, and non-commercialization. Geely and SAIC constitute a fourth group (limited Chinese sales) because they had low-volume sales, but were not mandated to commercialize an EV. Thus, they should not be categorized as either mass market or being driven by a technology-forcing policy. Table 3 identifies the breakdown of auto manufacturers in our sample according to these four categories.

Table 3.

Categorization of sample auto manufacturers according to their EV commercialization approach

| Mass market | Regulatory requirement | Non-commercialization | Limited Chinese sales |
|-------------|------------------------|-----------------------|-----------------------|
| BMW | Chrysler | Dongfeng | Geely |
| Daimler | Fiat | FAW | SAIC |
| Hyundai | Ford | Mazda | |
| Mitsubishi | GM | PSA | |
| Nissan | Honda | Suzuki | |
| Renault | Toyota | Tata | |
| Volkswagen | | | |

It is worth noting that every one of the LVM auto makers and all of the IVMs but Mazda have introduced a commercial EV. However, of auto manufacturers with LVM status, only Nissan has a mass market EV approach. The Nissan LEAF is available in 35 countries and has sold over 140,000 units. Other LVM auto makers generally only make their EVs available in section 177 states (those with ZEV regulations) and have sold less than 4,000 units.

2.1.3. Dependent variables

Dependent variables consisted of yearly counts of EV patents or prototypes for each firm in our sample. Patent data span 1991-2011 and came from Espacenet,⁶ which draws its information from several national databases. The patent figures for 2010 and 2011 being much higher than previous years indicates there is a low risk that the data was negatively affected by truncation (due to patent applications taking years to be granted). Data about prototypes (world-premiere concept vehicles) came from documentation of large auto shows around the world (Geneva, Detroit, Frankfurt, Paris, Tokyo, New Delhi, and Beijing) and spanned 1991-2013.⁷ Figures 2-5 provide descriptive analyses of the dependent variables used in our study.

Figure 2 shows the total number of patents filed by firms in our study. The number of EV patents has increased at a fairly steady pace throughout the study period until approximately 2007 when the rate of patent filing went up dramatically. This recent uptick in activity coincides with much more market activity in the EV market as auto makers have commercialized an increasing number of models (Sierzchula et al., 2012a).

⁶ <http://www.epo.org/searching/free/espacenet.html>

⁷ In instances where production EVs did not have an identifiable prototype date, the year they were first sold was used.

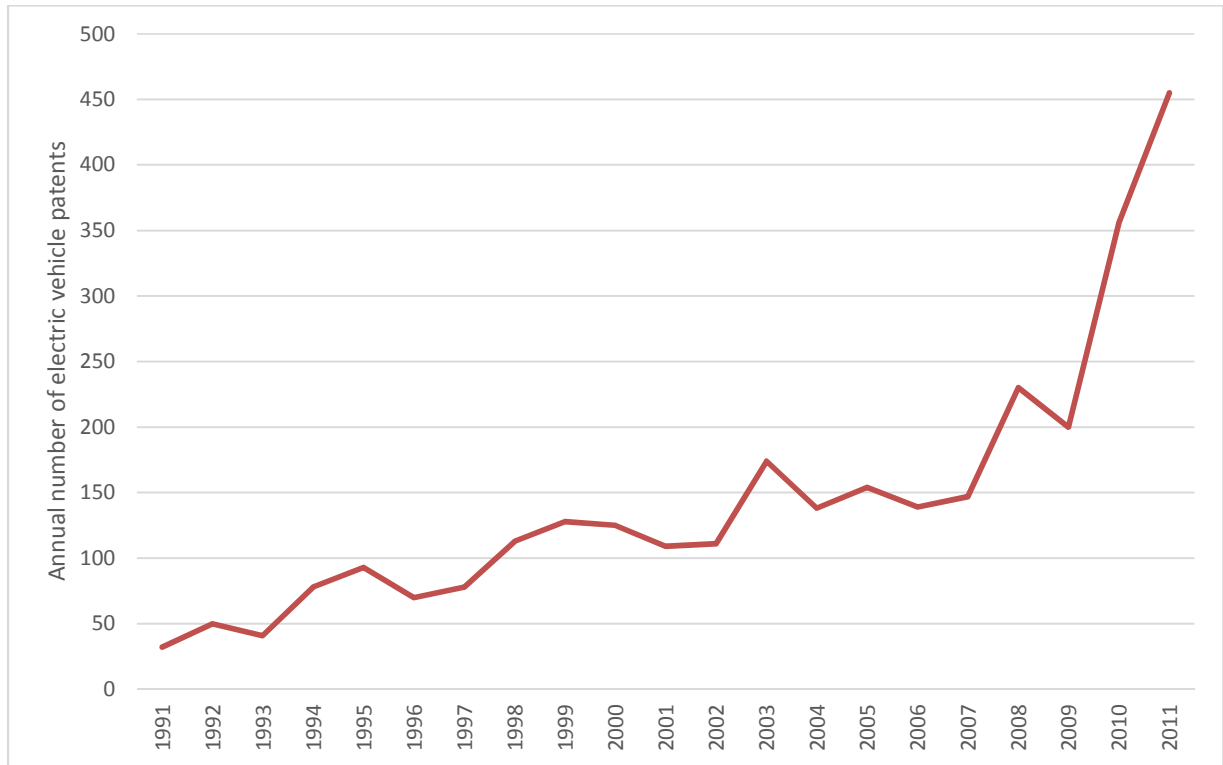


Figure 2. Annual total number of EV patents filed by firms in our study by submission year.

Figure 3 displays the annual EV patent counts of the top three patenting firms (Nissan, Mitsubishi, and Toyota). These manufacturers, specifically Toyota, followed roughly the same patenting pattern as that seen for the whole industry in Figure 2 with the general patenting trend increasing during the 2000s. One difference between these two figures is that patenting activity for manufacturers in Figure 3 picked up pace around 2000, several years earlier than it did for the industry in general. This suggests that these auto makers might be further along in their research and development of EVs than other firms in the sample.

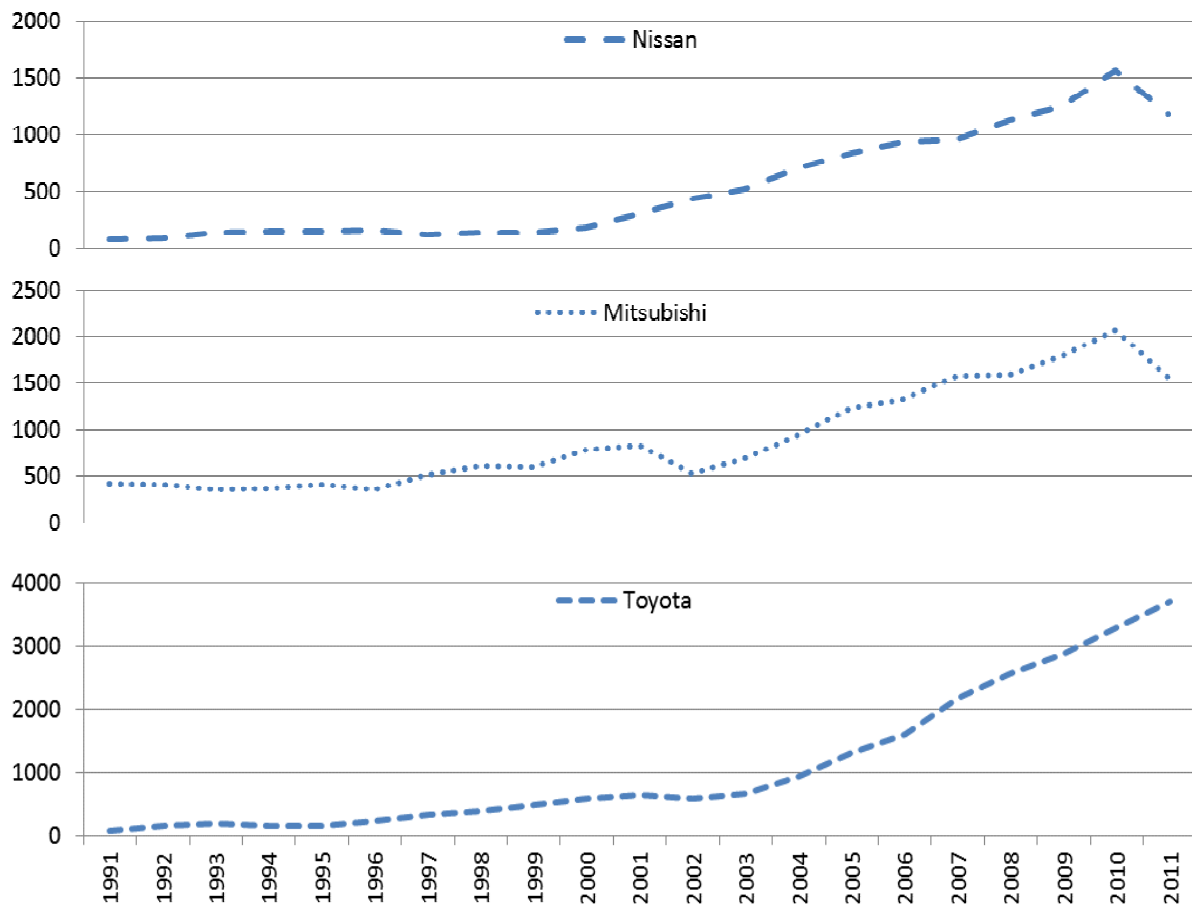


Figure 3. Top three patenting auto makers in our sample: patents per year by year of application.

Figure 4 shows the number of EV prototypes that were presented to the public by year. As opposed to the patent numbers, firm presentation of EV prototypes displayed a more boom and bust pattern. Auto manufacturers were actively presenting prototypes in the mid-1990s, basically stopped in the early 2000s, and then picked up again in 2006. Patents and prototypes also strongly differ in their recent history (specifically due to the time lag associated with patenting). Auto makers continued to increase their EV patenting through 2011 while the number of prototypes peaked in 2010 at 31 and then fell dramatically to 5 in 2013. This suggests that patents and prototypes may not follow the same trends and might in-fact be indicators for different elements of innovation.

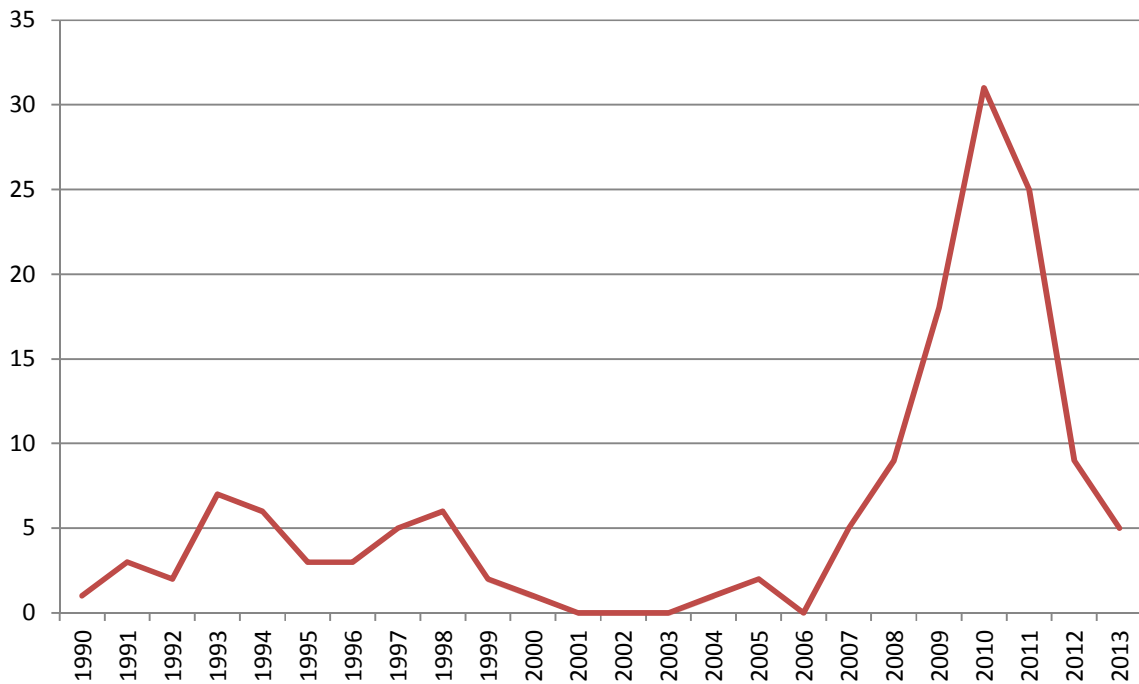


Figure 4. Total number of prototypes presented by sample firms in a given year.

Figure 5 shows the total number of EV patents and prototypes by firm during the study period, along with corresponding sales of their top-selling model (using the data from Table 2). Some companies like Toyota and Nissan had a high number of both prototypes and patents. Others car companies such as Daimler and Suzuki had a relatively high level of either one or the other indicator (prototypes and patents respectively). Most of the firms in this sample fit into the bottom left quadrant with a sum total of fewer than 5,000 patents and 10 prototypes. There appears to be a distinct difference in development strategies by region. Korean and Japanese firms generally produced higher patents rates, German manufacturers presented large numbers of prototypes, and auto makers from emerging countries had low levels of both indicators. Of particular note is the relatively weak correlation (0.189) between prototypes and patents for firms. The results from Figure 5 provide further evidence that patents and prototypes are two distinct innovation markers.

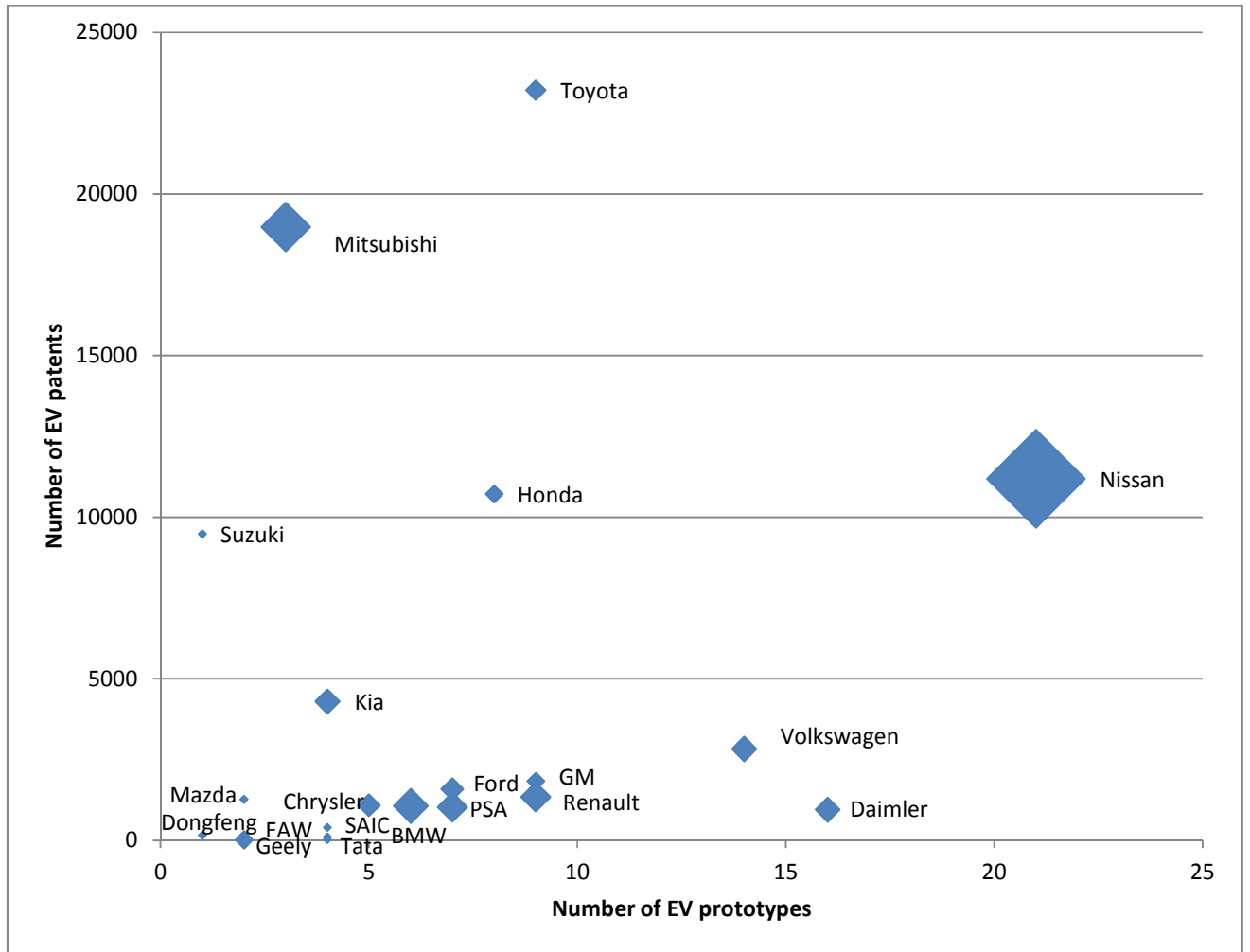


Figure 5. Total number of EV patents and prototypes by firm over the study period; size of diamond is relative to EV sales figures.

2.1.4. Independent variables

Table 3 shows the list of explanatory variables used in regression models for both patent and prototype analyses, along with the unit of measurement and source. Each of these variables controlled for important factors that previous studies have shown influence firm development of alternative fuel vehicles.

Table 3.

Explanation of independent variables used in regression models.

| Variable | Variable explanation and units used in the model | Source |
|------------------------------|---|-----------------------|
| Production | Manufacturer annual vehicle production ⁸ (100,000s of vehicles) | OICA, 2014 |
| CA sales | Annual vehicle sales by manufacturers in California ⁹ (10,000s of vehicles) | CARB, 2014c |
| Gas price | Average annual US gasoline price ¹⁰ (\$ per gallon) | EIA, 2014 |
| LVM dummy | Large volume manufacturer with annual vehicle sales > 60,000 (threshold depends on year) (0/1) | CARB, 2014c |
| IVM dummy | Intermediate volume manufacturer with between 4,501 – 60,000 annual vehicle sales (0/1) | CARB, 2014c |
| Policy stringency dummies | Identifies different ZEV policy regimes: Phase 1 (1991-2002); Phase 2 (2003-2008); Phase 3 (2009-2013) (0/1 for each phase) | CARB, 2014d |
| National HQ dummies | Identifies the location of the manufacturer's headquarters e.g. US, EU, Japan, Korea, India, or China (0/1) | Manufacturer websites |
| Mass Market dummy | Identifies whether auto makers took a mass market approach to EV commercialization as identified through sales > 5,000 and availability in more than five countries (0/1) | Manufacturer websites |
| Regulatory requirement dummy | Identifies auto makers that were required to sell EVs in order to meet ZEV regulation requirements and did not have a mass market approach to commercialization (0/1) | Manufacturer websites |
| Non-commercialization dummy | Identifies auto makers that have not introduced a commercial EV to the market (0/1) | Manufacturer websites |
| Limited Chinese sales dummy | Identifies auto makers that have introduced a commercial EV only in China and only on a limited scope (sales < 1,000) (0/1) | Manufacturer websites |

⁸ 1998-2013 vehicle production data came from OICA. Production statistics for years prior to 1998 were not available, so we used 1998 figures.

⁹ CA vehicle sales figures by manufacturer were only available since 2009. Years prior used 2009 figures.

¹⁰ Corrected for 2013 US dollars.

We included annual vehicle production¹¹ in our model because a firm's size has been shown to influence its R&D activities, specifically patenting (Ernst, 2001; Popp and Newell, 2009). In addition, we added a variable to identify the relative importance of the California market¹² for individual auto manufacturers. Previous research has shown that regulation of important auto markets can have a direct impact on firm R&D (Vogel, 1995; Bedsworth and Taylor, 2007). Annual US gas prices were incorporated in the model because fuel cost has been associated with increased adoption of energy-efficient vehicles (Diamond, 2009; Gallagher and Muehlegger, 2011), which in turn induces firm innovation (Newell et al., 1999).

LVM and IVM are dummy variables that identify to what extent auto manufacturers were subject to ZEV regulations.¹³ In our study, Mazda was only a LVM from 1991-1999. Its standing shifted to being an IVM when annual sales requirements for LVM status increased from 35,000 to 60,000 passenger cars in 2000. It is possible for firms to move from IVM to LVM status based on their number of annual vehicle sales, but this transition includes a five year lag period. The only such cases in our study were when Daimler merged with Chrysler and when Fiat merged with Chrysler.

Our model used a variable to gauge policy stringency because this dynamic has been shown to affect technological development (Ashford et al., 1985). California's ZEV legislation has experienced three distinct regimes relative to policy stringency. The first lasted from the introduction of ZEV regulations in 1991 until they were challenged in court in 2002. Thereafter, there was a period of steadily relaxing policy stringency until 2008. In 2009, the policy stringency increased as auto makers again had to use ZEV sales to meet ZEV credit requirements. Firm headquarters dummy variables (US, EU, China, Japan, Korea, or India) were used to help control for differences in nation-specific patenting rates. For example, in Japan, auto manufacturers have been shown to file and receive patents at a higher rate than car makers in other countries (Oltra and St. Jean, 2009).

The final set of variables allowed for distinction between different approaches to EV commercialization. More detailed explanation of these variables and how auto manufacturers fit into different commercialization categories is available in section 2.1.2 of the paper. In brief, commercialization approach was determined by the number of countries where an auto maker's top-selling EV model is available and the related number of sales. The categories for this dummy variable include: mass market, regulatory requirement, non-commercialization, and limited Chinese sales.

We chose not to include general firm R&D spending in our model because auto manufacturers do not break their R&D budgets down according to technology. Therefore, it was not possible to determine how much each of the firms in our sample spent on developing EV technologies during the study period. As a result, general firm R&D funding figures would not necessarily distinguish between a company like Nissan that has heavily invested in EV development and Mazda which has not (Sierzchula et al., 2012b).

¹¹ During the Chrysler and Daimler merger, we took the percent of vehicle production from 2006 (the first year where the companies had separate production figures) and applied it to previous years. Chrysler had 55% and Daimler 45%.

¹² The annual number of California vehicle sales was used as a proxy for the ZEV market because it was not possible to attain vehicle sales data from each of the 177 states.

¹³ In our study, firm ZEV status was operationalized as LVM, IVM, or nothing. LVM firms were not included in the IVM group.

2.2. Specification of regression model

Fixed effects (FE) and random effects (RE) models are two standard approaches for analyzing panel data (Hsiao, 1985). A FE model employs time-invariant characteristics, e.g., gender or race, giving each case its own error term and constant, and thus helping to control for omitted variables. In effect, this type of model uses individual subjects as their own controls and is especially suited to analyze variables that vary within a case over time such as age or income (Allison, 2009). A RE model assumes that a case's error term is not correlated with predictors, which allows time invariant characteristics to be explicitly used as explanatory variables (whereas they would be absorbed into FE models). As such, RE models are more appropriate for analyzing the specific effect of a time-invariant variable.

We elected to use a RE model for two primary reasons. Firstly, Hausman tests indicated that there is no difference between the coefficients of fixed effects and random effects estimators. Thus it was possible for us to use the more efficient Random Effects estimator.¹⁴ Secondly, because of fundamental characteristics of the main variables that this study sought to explore. The primary relationship that the first hypothesis seeks to test (the correlation between auto manufacturer LVM/IVM status and its R&D performance) was a time-invariant variable for the vast majority of the firms in our sample. Similarly the primary relationship for the second hypothesis (the correlation between auto maker approach to EV commercialization and its R&D performance) was time-invariant for all of the firms in our sample. Because these important variables did not change over the course of study period (or only did so in rare cases), a FE model would not be able to capture their effect on firm R&D. Thus a RE model was the most appropriate statistical test for our particular data set.

The RE model for the first hypothesis (analyzing ZEV status) can be expressed as:

$$Y_{it} = \alpha + \beta_1 X_{it} + \beta_2 \delta_{it} + u_i + \varepsilon_{it}$$

The RE model for the second hypothesis (analyzing EV commercialization approach) can be expressed as:

$$Y_{it} = \alpha + \beta_1 X_{it} + \beta_2 \gamma_{it} + u_i + \varepsilon_{it}$$

Where Y_{it} is the number of EV patents received or prototypes presented by firm i in year t and α is the constant. X_{it} is a vector of observations on coordinates that affect Y_{it} including gas prices, California sales, annual vehicle production, policy stringency, and the location of the firm's headquarters. For the first hypothesis, the analysis focuses on an estimate of δ_{it} , a vector of dummy observations that indicates the status a firm was designated by ZEV regulation. For the second hypothesis, the analysis focuses on the γ_{it} , vector of dummy observations that identifies different approaches auto makers have taken regarding EV commercialization. The variable u_i represents a group-specific random element (which is necessary for analyzing panel data). Finally, ε_{it} is the model's error term.

¹⁴ Hausman test values for patent analyses were .25 for ZEV regulations and .37 for commercialization. Values for prototype analyses were .20 for ZEV regulations and .57 for commercialization.

Since the study used count data with a large number of zero values, it was not possible to transform the figures to have a normal distribution, violating an OLS assumption. Both Poisson and negative binomial RE models are suitable to analyze the patent and prototype count data that this study uses. However, because both data sets were overdispersed (their variances were higher than their means), negative binomial models were preferable. Evidence of autocorrelation and heteroskedasticity in the data indicated that models should include manipulation of standard errors to correct for these issues. Following Flachaire (1999), we used paired bootstrapping of standard errors in our models to address autocorrelation and heteroskedasticity. Tests for multi-collinearity resulted in an aggregate variance inflation factor (VIF) of approximately 4 with no VIFs higher than 10, suggesting that this problem was not present in our data.¹⁵

3. Results

This section includes the results from RE negative binomial regressions of patents and prototypes as they relate to auto maker ZEV status and EV commercialization from 1991-2013. To help minimize the impact of truncation, patent analyses were only conducted through 2011. Descriptive statistics for each model are available in Appendices 1-4.

3.1. ZEV regulations analysis

The ZEV regulations analysis shows whether auto makers categorized as LVMs, and thus needing to sell a set number of EVs, were more likely to have higher numbers of patents and prototypes than car companies that were not faced with these regulatory requirements. Additional explanatory variables such as policy stringency (whether the ZEV regulations actually incorporated an EV sales requirement), the price of gasoline, production statistics, California auto sales, and national location of auto maker headquarters were included in regressions to correct for other potentially influential factors. Table 4 provides ZEV regulations regression results for patents and prototypes in Models 1 and 2 respectively.

Table 4: ZEV status regressions.

| | Patents (Model 1) | Prototypes (Model 2) |
|---------------|----------------------|-------------------------|
| Production | 0.010 (0.006) | 0.014 (0.011) |
| CA sales | -0.008 (0.033) | -0.025 (0.042) |
| LVM status | 0.367 (0.460) | 0.92 (2.921) |
| IVM status | 0.430 (0.443) | 0.342 (3.021) |
| EU firm | 0.497 (0.510) | 0.808 (2.910) |
| Japanese firm | 1.414 (0.532)** | 0.409 (0.410) |
| Chinese firm | -2.052 (0.735)** | -0.058 (2.997) |
| Korean firm | 0.235 (0.493) | -19.06 (1.913)** |
| Indian firm | -2.020 (0.525)** | -18.60 (3.198)** |
| Gas price | 0.334 (0.061)** | -0.004 (0.003) |
| Phase 2 | 0.541 (0.111)** | -0.130 (0.299) |

¹⁵ Indices of collinearity are available in Appendices 5 and 6.

| | | |
|----------------|-----------------|-----------------|
| Phase 3 | 1.064 (0.116)** | 2.018 (0.399)** |
| N | 441 | 483 |
| Log likelihood | -2008.71 | -253.85 |

** P<.01

* P<.05

Model 1 shows a positive but not significant relationship between auto manufacturers subject to ZEV regulation and the number of EV patents they received. Gas prices, policy stringency, and national headquarters location were found to be significant predictors of EV patenting. Both second (2003-2008) and third (2009-2011) ZEV policy regimes had a positive relationship to the number of EV patents that the firms submitted. The coefficient for the third policy phase was twice as high as that of the second, which indicates that auto makers have been increasing the number of EV patents that they file, confirming the trend observed in Figure 2. The national headquarters location had a negative impact for Chinese and Indian auto makers; this relationship was positive for Japanese and Korean car companies. Table 4 identifies a strong difference in EV patenting between auto makers from different countries.

Model 2 shows only three variables that were statistically significant predictors of EV prototypes during the study period: Korean Firm, Indian Firm, and Phase 3. Both Korean and Indian firm variables were negatively correlated to prototypes while the most recent phase of ZEV regulations had a positive relationship. These results suggest that ZEV regulations do not have a strong connection to firms' patenting EV-related technology. Instead, EV patenting appears to be correlated to wider socio-technical factors such as gas price and national location of auto maker headquarters.

3.2. EV commercialization analysis

The EV commercialization analysis shows the extent to which patents and prototypes are correlated to specific market introduction approaches chosen by auto makers. Similar to the ZEV regulations regression, the EV commercialization analysis included the following additional explanatory variables: policy stringency, gasoline price, production statistics, California auto sales, and national location of auto maker headquarters. Table 5 presents coefficients, standard errors, and statistical significance for both patent and prototype analyses relative to auto maker EV commercialization approaches.

Table 5: Auto maker EV commercialization approach regressions

| | Patents (Model 3) | Prototypes (Model 4) |
|----------------|----------------------|-------------------------|
| Production | 0.009 (0.006) | 0.001 (0.005) |
| CA sales | -0.044 (0.025) | 0.044 (0.029) |
| Mass market | 1.027 (0.381)** | 0.998 (0.44)* |
| Compliance car | 1.613 (0.450)** | -0.409 (0.736) |
| Chinese model | -0.856 (0.703) | 0.722 (0.826) |
| EU firm | 0.686 (0.413) | -0.509 (0.476) |
| Japanese firm | 1.953 (0.533)* | -0.557 (0.517) |

| | | |
|----------------|------------------|-----------------|
| Chinese firm | -0.948 (0.859) | -1.132 (0.926) |
| Korean firm | 0.588 (0.488) | -23.89 (1.913) |
| Indian firm | -1.214 (0.529)** | -22.36 (3.198) |
| Gas price | 0.349 (0.052)** | -0.003 (0.002) |
| Phase 2 | 0.53 (0.109)** | 1.925 (0.426)** |
| Phase 3 | 1.099 (0.109)** | 0.001 (0.005) |
| N | 441 | 483 |
| Log likelihood | -1996.33 | -249.97 |

** P<.01

* P<.05

In Model 3, both mass market and compliance car variables were found to be statistically significant and positive, suggesting that auto makers with those EV commercialization approaches were likely to have a higher number of patents than were the other car companies in the study. Variable coefficients indicated that auto makers with a regulatory requirement to commercialize EVs had a higher patent count than did car companies seeking a mass market approach. Other significant variables in Model 3 included Japanese firm, Indian firm, Gas price, and both policy regimes. Similar to Model 1, Phase 3 of the ZEV regulations was correlated with substantially higher patent levels than was Phase 2.

The significant variables for Model 4 included mass market and Phase 3 of the ZEV regulations. This makes logical sense as those companies seeking to introduce a commercial EV to the mass market would likely go through a lengthy prototype phase with multiple models as seen with the Nissan LEAF and Mitsubishi i-MiEV. These results suggest that technology-forcing requirements do not have a strong correlation to the number of prototypes that auto makers present to the public. Instead, EV prototypes have been presented to the public during the most recent phase of ZEV regulations, and specifically by those firms seeking to engage the mass market with their models.

3.3. Study concerns and limitations

The limitations of this research stem from it being a case study that only analyzes the impact of ZEV regulations on EV development. Consequently, our results may have limited applicability in other cases. Furthermore, since the development of a radical innovation is so uncertain and involves influences from many different sources, we cannot be sure that the model contained the most relevant and important variables. For example, factors such as country-level financial incentives can and likely have influenced EV development for specific auto makers. However, it is important for innovation policymakers to have a good understanding of how technology-forcing policies influence firm innovation, and even with this study's limitations, it provides useful analysis. In particular, adding a global element to the analysis allows for a much better explanation of how technology-forcing policies influence firm patenting activity relative to radical innovation.

4. Discussion

The introduction presented two hypotheses, that technology-forcing policies (in the form of ZEV regulations) would lead to higher auto maker patent and prototype numbers, and that increasing firm R&D levels would correspond to the following strategies for EV market introduction: avoiding commercialization all together; seeking to meet a regulatory requirement; and a mass market approach. While results from the panel analysis provide evidence against both of these hypotheses, they do give insight into how patents could be used to meet the study's research objective – identification of a preliminary indicator that can help gauge the effectiveness of a technology-forcing policy. In addition, the results also call in question the efficiency of ZEV regulations in reducing transportation emissions.

Table 4 indicates that ZEV regulations have not been successful in encouraging auto makers to file EV patents or publically introduce prototypes. Although all of the LVMs and the vast majority of IVMs have marketed a commercial EV, patents and prototypes were not found to be good precursor indicators for measuring the effectiveness of the technology-forcing policy. Instead of being driven by ZEV regulations, those R&D markers were more strongly correlated to long-term trends such as rising fuel prices, and ZEV policy stringency.

However, just analyzing auto makers according to their LVM/IVM status, as the ZEV regulation regressions did, does not provide a good explanation of R&D activity for many cases where car companies sought to introduce EVs on a mass market scale e.g., BMW, Mitsubishi, and Renault. According to Table 3, there were eight such companies, only one of which had LVM status (Nissan). These auto makers, who have introduced a commercial EV even though they are not compelled to do so by ZEV regulations, account for a large number of prototypes and patents in our study. Thus, it is not surprising that Table 4 did not identify a correlation between R&D and ZEV regulations. Once different commercialization strategies were included in the analysis, then ZEV regulations along with a mass market approach were found to be statistically significant in explaining auto maker patent levels. Conversely, the incorporation of EV commercialization variables did not help to explain the number of prototypes that auto makers introduced to the public. Combining the results from Tables 4 and 5 suggests that prototypes are not a good indicator for technology-forcing policies, while patents may be if they are incorporated in a global context where firms may have heterogeneous approaches to commercialization.

The results in Table 5 bring into question why auto firms merely seeking to meet ZEV regulations had higher patent figures than those that chose a mass market commercialization approach. It is possible that this difference is due to compliance car companies' broader interest in electric mobility and other market activities. For example, for over a decade Toyota has focused on developing hybrid-electric vehicles (HEVs) and in 2015 will introduce the Mirai, a mass market hydrogen fuel-cell vehicle. GM, on the other hand has devoted significant resources to developing and marketing plug-in hybrid-electric vehicles (PHEVs), notably the Chevy Volt. Ford has also introduced mass market PHEVs in the form of the C-Max Energi and Fusion Energi. Thus, even though auto makers have introduced compliance cars to meet the ZEV regulatory minimum, they have still heavily invested in electric mobility R&D, which explains their high patent figures.

Results in Table 5 also bring into question the broader policy aim of ZEV regulations. We speculate that ZEV regulations may be causing auto makers to commercialize EVs that they otherwise would not. Consequently, LVMs that have had to sell EVs to meet ZEV regulations are likely bearing high prices associated with commercializing a radical innovation before it is cost effective, exemplified by Fiat's CEO claiming that the car company loses \$14,000 on each 500e that it sells (Henkel, 2014). Also, it is likely that many of the LVMs (except for Nissan) have responded to ZEV requirements through reducing the available EV stock and ultimately limiting their losses as much as possible, which explains the low sales figures for many of the compliance cars in Table 1. A relevant policy question would be the extent to which ZEV regulations are in fact reducing transportation emissions through encouraging the market introduction of a few compliance EVs. Perhaps transportation emissions reductions could be more effectively achieved by allowing auto makers to expand their current mass market technologies e.g., HEVs, PHEVs, and FCEVs, instead of forcing them to spend resources developing and marketing a low-volume EV. Reducing greenhouse gas emissions is a worthy goal, but it could turn out that ZEV regulations have not been the most effective policy to achieve this aim.

5. Conclusions and policy implications

Technology-forcing regulations have been shown to be effective tools in driving innovation, but using this type of policy entails a high level of uncertainty and thus requires close communication between regulators and firms. The need for dialogue is heightened when policies target creation of radical innovations that require an extended period of time development and commercialization. In such situations, it may not be possible for regulators to examine a final commercial product in the early years of the policy's existence. During pre-commercial development, information asymmetries between policymakers and industry representatives may lead the regulators to have an inaccurate understanding of the effectiveness of the policy.

In analyzing the influence of ZEV regulations on the development and commercialization of EVs, our study sought to determine to what extent patents and prototypes could serve as good preliminary measures of the effectiveness of technology-forcing legislation. Based on the case study results, firms that need to commercialize an innovation to meet regulatory requirements and those that take a mass market approach will have higher levels of patents than will other companies in the industry. The primary conclusion from this result is that patent counts can be a useful indicator for technology-forcing regulations when imbedded in a global industrial perspective, and thus could help correct for information asymmetries when policymakers gauge the early effectiveness of a particular policy.

The study's two secondary conclusions are that prototypes are not good measures of technology-forcing regulations and that global industrial dynamics need to be incorporated into an analysis of policies from individual markets. Based on our case study, analyzing the impact of a technology-forcing regulation on firm R&D from the perspective of a single market within a broader global industry results in a skewed understanding of the impact of the policy. The patenting activity of auto makers such as BMW and Renault was better explained once we incorporated a global perspective and determined that the firms have taken a mass market approach to EV commercialization, instead of only relying on their status as identified by ZEV regulations.

While technology-forcing policies may be an effective approach in pushing innovation, they are, as noted by Jaffe et al. (2003), a very costly one. Though technology-forcing legislation often results in more deadweight loss than other policy instruments, it is important to note that they can shift costs from the government to manufacturers. As a result, in environments of public sector austerity and limited resources, they may represent the most pragmatic policy instruments for encouraging radical innovation. The results from this study suggest that patents can be a useful tool for decision-makers to gauge the progress of companies toward goals associated with technology-forcing regulations. And while policymakers analyzing the effectiveness of a technology-forcing policy should not depend too much on patents, they should help correct for some of the information asymmetries that exist between regulators and firms during assessment of early innovation development.

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Appendix

Appendix 1. ZEV regulations patent descriptive statistics

| | Unit | N | Mean | Std. Dev. | Min | Max |
|---------------|----------------------|-----|-------|-----------|------|-------|
| Patent | # of patents | 441 | 208 | 431.67 | 0 | 3699 |
| Production | Vehicles in millions | 441 | 25.76 | 22.61 | 0.91 | 93.49 |
| CA sales | Vehicles in 10,000s | 441 | 4.78 | 6.65 | 0 | 31.70 |
| Gas price | \$ per gallon | 441 | 2.21 | 0.67 | 1.45 | 3.67 |
| LVM status | Y/N (0/1) | 441 | 0.33 | 0.47 | 0 | 1 |
| IVM status | Y/N (0/1) | 441 | 0.25 | 0.44 | 0 | 1 |
| EU firm | Y/N (0/1) | 441 | 0.31 | 0.46 | 0 | 1 |
| US firm | Y/N (0/1) | 441 | 0.16 | 0.37 | 0 | 1 |
| Japanese firm | Y/N (0/1) | 441 | 0.29 | 0.45 | 0 | 1 |
| Chinese firm | Y/N (0/1) | 441 | 0.19 | 0.39 | 0 | 1 |
| Korean firm | Y/N (0/1) | 441 | 0.05 | 0.21 | 0 | 1 |
| Phase 1 | Y/N (0/1) | 441 | 0.57 | 0.5 | 0 | 1 |
| Phase 2 | Y/N (0/1) | 441 | 0.29 | 0.45 | 0 | 1 |
| Phase 3 | Y/N (0/1) | 441 | 0.14 | 0.35 | 0 | 1 |

Appendix 2. EV Commercialization patent descriptive statistics

| | Unit | N | Mean | Std. Dev. | Min | Max |
|-----------------------|----------------------|-----|--------|-----------|------|-------|
| Patent | # of patents | 441 | 208.00 | 431.67 | 0 | 3699 |
| Production | Vehicles in millions | 441 | 25.76 | 22.61 | 0.91 | 93.49 |
| CA sales | Vehicles in 10,000s | 441 | 4.78 | 6.65 | 0 | 31.7 |
| Gas price | \$ per gallon | 441 | 2.21 | 0.67 | 1.45 | 3.67 |
| Mass Market | Y/N (0/1) | 441 | 0.38 | 0.49 | 0 | 1 |
| Chinese model | Y/N (0/1) | 441 | 0.10 | 0.29 | 0 | 1 |
| Compliance car | Y/N (0/1) | 441 | 0.24 | 0.43 | 0 | 1 |
| Non-commercialization | Y/N (0/1) | 441 | 0.24 | 0.43 | 0 | 1 |
| EU firm | Y/N (0/1) | 441 | 0.31 | 0.46 | 0 | 1 |
| US firm | Y/N (0/1) | 441 | 0.16 | 0.37 | 0 | 1 |
| Japanese firm | Y/N (0/1) | 441 | 0.29 | 0.45 | 0 | 1 |
| Chinese firm | Y/N (0/1) | 441 | 0.19 | 0.39 | 0 | 1 |
| Korean firm | Y/N (0/1) | 441 | 0.05 | 0.21 | 0 | 1 |
| Phase 1 | Y/N (0/1) | 441 | 0.57 | 0.50 | 0 | 1 |
| Phase 2 | Y/N (0/1) | 441 | 0.29 | 0.45 | 0 | 1 |
| Phase 3 | Y/N (0/1) | 441 | 0.14 | 0.35 | 0 | 1 |

Appendix 3. ZEV regulations prototype descriptive statistics

| | Unit | N | Mean | Std. Dev. | Min | Max |
|------------|----------------------|-----|--------|-----------|------|-------|
| Prototypes | # of prototypes | 483 | 0.26 | 0.69 | 0 | 6 |
| Production | Vehicles in millions | 483 | 26.66 | 23.43 | 0.91 | 101.0 |
| CA sales | Vehicles in 10,000s | 483 | 4.99 | 6.86 | 0 | 31.7 |
| Gas price | \$ per gallon | 483 | 233.52 | 75.65 | 146 | 372 |
| LVM status | Y/N (0/1) | 483 | 0.33 | 0.47 | 0 | 1 |
| IVM status | Y/N (0/1) | 483 | 0.27 | 0.44 | 0 | 1 |

| | | | | | | |
|---------------|-----------|-----|------|------|---|---|
| EU firm | Y/N (0/1) | 483 | 0.31 | 0.46 | 0 | 1 |
| US firm | Y/N (0/1) | 483 | 0.15 | 0.36 | 0 | 1 |
| Japanese firm | Y/N (0/1) | 483 | 0.29 | 0.45 | 0 | 1 |
| Chinese firm | Y/N (0/1) | 483 | 0.19 | 0.39 | 0 | 1 |
| Indian firm | Y/N (0/1) | 483 | 0.05 | 0.21 | 0 | 1 |
| Korean firm | Y/N (0/1) | 483 | 0.05 | 0.21 | 0 | 1 |
| Phase 1 | Y/N (0/1) | 483 | 0.52 | 0.50 | 0 | 1 |
| Phase 2 | Y/N (0/1) | 483 | 0.26 | 0.44 | 0 | 1 |
| Phase 3 | Y/N (0/1) | 483 | 0.22 | 0.41 | 0 | 1 |

Appendix 4. EV commercialization prototype descriptive statistics

| | Unit | N | Mean | Std. Dev. | Min | Max |
|-----------------------|----------------------|-----|--------|-----------|------|-------|
| Prototypes | # of prototypes | 483 | 0.26 | 0.69 | 0 | 6 |
| Production | Vehicles in millions | 483 | 26.66 | 23.43 | 0.91 | 101.0 |
| CA sales | Vehicles in 10,000s | 483 | 4.99 | 6.86 | 0 | 31.7 |
| Gas price | \$ per gallon | 483 | 233.52 | 75.65 | 146 | 372 |
| Mass market | Y/N (0/1) | 483 | 0.381 | 0.486 | 0 | 1 |
| Chinese model | Y/N (0/1) | 483 | 0.095 | 0.294 | 0 | 1 |
| Compliance car | Y/N (0/1) | 483 | 0.244 | 0.430 | 0 | 1 |
| Non-Commercialization | Y/N (0/1) | 483 | 0.190 | 0.393 | 0 | 1 |
| EU firm | Y/N (0/1) | 483 | 0.31 | 0.46 | 0 | 1 |
| US firm | Y/N (0/1) | 483 | 0.15 | 0.36 | 0 | 1 |
| Japanese firm | Y/N (0/1) | 483 | 0.29 | 0.45 | 0 | 1 |
| Chinese firm | Y/N (0/1) | 483 | 0.19 | 0.39 | 0 | 1 |
| Indian firm | Y/N (0/1) | 483 | 0.05 | 0.21 | 0 | 1 |
| Korean firm | Y/N (0/1) | 483 | 0.05 | 0.21 | 0 | 1 |
| Phase 1 | Y/N (0/1) | 483 | 0.52 | 0.50 | 0 | 1 |
| Phase 2 | Y/N (0/1) | 483 | 0.26 | 0.44 | 0 | 1 |
| Phase 3 | Y/N (0/1) | 483 | 0.22 | 0.41 | 0 | 1 |

Appendix 5. Indices of collinearity for Model 1

| | VIF | 1/VIF | R ² |
|------------|------|-------|----------------|
| Chinese | 7.74 | 0.13 | 0.871 |
| Japanese | 5.75 | 0.17 | 0.826 |
| EU | 5.59 | 0.18 | 0.821 |
| LVM | 5.07 | 0.2 | 0.803 |
| Ca sales | 4.97 | 20 | 0.799 |
| Production | 4.58 | 0.21 | 0.782 |
| Gas price | 3.82 | 0.26 | 0.738 |
| Phase 2 | 2.98 | 0.34 | 0.664 |
| Phase 3 | 2.93 | 0.34 | 0.659 |
| Indian | 2.89 | 0.35 | 0.654 |
| Korean | 2.41 | 0.42 | 0.585 |
| IVM | 1.98 | 0.5 | 0.495 |

Mean VIF 4.23

Appendix 6. Indices of collinearity for Model 3

| | VIF | 1/VIF | R ² |
|----------------|------|-------|----------------|
| Chinese firm | 9.36 | 0.11 | 0.893 |
| Japanese firm | 8.18 | 0.12 | 0.878 |
| Compliance car | 7.59 | 0.13 | 0.868 |
| EU firm | 6.77 | 0.15 | 0.852 |
| CA sales | 6.12 | 0.16 | 0.837 |
| Production | 4.31 | 0.23 | 0.768 |
| Gas price | 3.81 | 0.26 | 0.738 |
| Indian firm | 3.24 | 0.31 | 0.691 |
| Mass market | 3.11 | 0.32 | 0.678 |
| Phase 2 | 2.98 | 0.34 | 0.664 |
| Phase 3 | 2.92 | 0.34 | 0.658 |
| Mean VIF | 4.84 | | |
