Regulation Timing on Green Innovation: The Case of Vehicle Emissions

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Abstract

As environmental issues become increasingly addressed globally, the discussion on effective strategic incentives to regulation becomes increasingly relevant. Here we study the case of vehicle emissions regulations and provide evidence that there are decreasing returns to late regulation implementation. Vehicle emission regulations are adopted in a large set of countries, they undergo multiple levels of stringency and are relatively comparable between countries - as such, they provide a good setting for studying this topic. Through the use of patent data we build innovation indicators as well as proxies for regulation specific market sizes at the firm level. These are used to investigate the push and pull dynamics of innovation creation. Additionally, different emissions control technologies are examined individually and surprisingly, despite their different characteristics, they give similar results.

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1 Overview

Can environmental policy be a driver of firm innovation? In what form (direction, scale, etc.) and under what conditions (timing, policy structure, leader, firm size, etc.) can this happen? We attempt to answer these questions through the lens of vehicle emissions regulations. Historically, the introduction of environmental regulations were viewed negatively by firms as they believed it would increase costs and cause a general trade off in global competitiveness. A literature in the early 90s, beginning with Michael Porter, argued that well designed regulations can in fact increase firm competitiveness by catalyzing innovation to a degree that can offset the costs of regulation. This argument has been adopted in the United States and other countries to push through tougher regulations. The empirical evidence on Porter's Hypothesis[14] generally agrees that innovation activity increases due to changes in regulation, however some sectors are exceptions and the effect on competitiveness is inconclusive.

Here we study the case of vehicle emissions regulations and provide evidence that innovation increases by being a regulatory early mover. Vehicle emission regulations are adopted in a large set of countries, they undergo multiple levels of stringency and are relatively comparable between countries - as such, they provide a good setting for studying this topic. A data collection effort was made to gather information on historical vehicle emission regulations. We build innovation indicators with the use of patent data. These are used to measure the market size and timing effects and investigate the push and pull dynamics of innovation creation. Additionally, different emissions control technologies are examined individually and surprisingly, despite their different characteristics, they give similar results.

In international trade, when one country imposes a regulation, for example, minimum quality and safety requirements on seatbelts, this increases the costs of firms producing in that country as opposed to firms in countries with less stringent seatbelt regulations. Everything else equal, this would mean a lower competitiveness for the firms in the country with more seatbelt regulations. Environmental regulations are however different in that their dynamics over time have some certainty due to externalities on other countries. Therefore there is pressure from the international community to collectively increase regulation stringency. We can generally expect environmental regulations to become more stringent overtime as climate change increases in severity and international organizations increase pressure on countries to reduce emissions. While firms in countries that do not currently impose stringent seatbelt regulations have little reason to expect seatbelt regulations to increase in the near future. The more certain future expectations of environmental regulations suggest a potential benefit to strategically timing country regulatory entry.

Vehicle emission regulations impose an upper limit on the amount of pollutants that can be emitted from a car in every day use. These are enforced with driving tests that simulate everyday driving conditions that must be conducted before a new car model enters the market. These regulations are colloquially called standards although they are typically imposed by air quality agencies, federal transportation agencies or in the case of the EU, through EU directives and regulations.

In terms of environmental regulations, the transportation sector is usually treated separately from the rest of industry because the final amount of emissions results from consumer use. As opposed to the rest of industry for which CO_2 emissions are emitted during the production process, regulations in the transportation sector have to be imposed on the product itself. In the sense of Romer (1990)[15] this implies a new product variety. Also, as previous vehicles and technologies become obsolete we encounter a situation of essentially mandated creative destruction as in Schumpeter and Aghion and Howitt (1992)[2].

A country may want to develop the relevant technologies earlier and therefore implement environmental regulations early as it is likely it's domestic multinational firms will benefit for a longer time as other countries adopt later. We refer to this as the temporal dimension to regulations. Foreign firms with production in this country then have to decide whether they want to take on the costs and maintain a position in this country's market. As such, adopting a new regulation imposes a kind of trade barrier. In particular, there is evidence that large domestic firms often communicate with their country's government on a timing and scope that benefits them.[1] When there is a dialogue between domestic firms and government, we expect large domestic firms may have an impact on the regulation implementation timing while small domestic firms and foreign firms are forced to adapt.

On the other hand, there may be high costs associated with the development of the new technologies. These costs generally decrease as a knowledge stock forms for the technology. Thus from this perspective, countries also have an incentive to free ride and adopt the regulation later. Dechezlepretre and Glachant (2014)[7] study the different effects of domestic versus foreign policies on innovation in the wind industry.

Section 2 below gives an overview of the regulatory and patent datasets, section 3 describes the empirical model, section 4 presents our main results, robustness checks, a technology breakdown and results stratified by firm size; section 5 concludes.

2 Data Description

2.1 Regulation Data

A combination of air pollution concerns led to the Air Pollution Control Act of 1955 in the United States which was signed into law by Eisenhower on July 14, 1955. At this time, the scope was simply to "provide research and technical assistance relating to air pollution control" and the act mostly called on states to take charge and prevent air pollution at the source. It wasn't until 1963 that the first version of a federal legislation: the Clean Air Act (CAA) was instated and only in 1968 did the CAA amendments include a provision on vehicle emission limits. The first substantially stringent limits were passed in 1970 and required emission reductions of 90% from the levels at the time. Implementation had been scheduled to take effect in 1975 but were

[1] see Zingales (2017) [17]

delayed due to technology limitations and were instead implemented progressively with full scale being reached in 1979.

In parallel, vehicle emissions legislation was beginning in other countries as well. Notably Japan first introduced carbon monoxide (CO) emissions in 1966. They then announced limits on CO, hydrocarbons (HC) and nitrous oxides (NOx) in 1970 with an implementation date of 1973. However with the Muskie proposals and the announcement of substantially more stringent regulations in the US, the Japan Central Council for Environmental Pollution Control responded with a proposal for more stringent exhaust emission standards in 1971. These limits were set in 1975 and remained for sixteen years although revisions to test procedures effectively made them more severe.

Emissions standards in Europe were first formulated by the United Nations Economic Commission for Europe (UN-ECE). However the UN-ECE has no enforcement power and therefore relies on the individual member countries to adopt and enforce the regulations. The first framework for vehicle regulations was set in 1970 with the 70/220/EEC Directive. This was the first to outline a test procedure and made reference to an end-of-pipe air filter technology for the exhaust system although the purpose of this directive targeted vehicle sound pollution. Limits on pollutant emissions were officially introduced on June 26, 1991 with Council Directive 91/441/EEC - globally known as Euro 1 - amending Directive 70/220/EEC. This defines the scope of our regulatory variable:

"This Directive applies to the tailpipe emissions, evaporative emissions, emissions of crankcase gases and the durability of anti-pollution devices for all motor vehicles equipped with positive ignition engines and to the tailpipe emissions and durability of anti-pollution devices from vehicles of categories M1 and N1 (1), equipped with compression-ignition engines covered by Article 1 of Directive 70/220/EEC in the version of Directive 83/351/EEC (2), with the exception of those vehicles of category N1 for which type-approval has been granted pursuant to Directive

Tier	Date	CO	THC	NMHC	NOx	HC+NOx	PM	PN [#/km]
Euro 1	07/1992	2.72	-	-	-	0.97	-	-
Euro 2	01/1996	2.2	-	-	-	0.5	-	-
Euro 3	01/2000	2.3	0.2	-	0.15	-	-	-
Euro 4	01/2005	1	0.1	-	0.08	-	-	-
Euro 5	09/2009*	1	0.1	0.068	0.06	-	0.005**	-
Euro 6	09/2014	1	0.1	0.068	0.06	-	0.005**	610^{11}

Table 1: EU emissions standards for passenger cars (M1):
Table from: https://www.dieselnet.com/standards/eu/ld.php
Note that prior to Euro 5, passenger vehicles above 2500 kg were type approved as category N1 vehicles. Measurement units for CO, THC, NMHC, NOx, and PM are in g/km.
* 01/2011 for all models
** Applies only to vehicles with direct injection engines

88/77/EEC"

The baseline EU regulations set limits for different pollutants measured in g/km, as shown in Table 1. Our final regulatory dataset was selected to cover 95% of global vehicle and vehicle parts imports.[2]

Starting from the regulatory dataset used in Perkins and Neumayer (2012)[13], we updated and expanded the information to cover more countries and more years. Some sites and organizations tracking this information are: Concawe, Transport policy, MECA, CAI for Asia, UNEP, etc.. However the information is often incomplete and sometimes inconsistent between sources so we often dive deeper into the respective problem countries and look for original regulatory documents.[3]. This, of course, is a constant work in progress as we do not claim to have found the entire population of regulatory documents.

The problem with not having a full population of documents is that we cannot guarantee the dates that we have noted. Our regulatory dataset is constructed from implementation dates however sometimes we only have the announcement document that specifies an implementation date. In reality that implementation date may have changed and is in fact rather frequently

[2]Measured from CEPII's Baci trade dataset at the HS6 level. This captures 75 countries.
[3]See Appendix E for the various sources. The set of documents collected will be eventually available online

delayed for various reasons. If we do not find the document for the date change/delay, then we do not have the correct implementation date in our dataset. At the same time, one can argue that the announced implementation date is the most important date as it is the date firms expect apriori and is arguably the schedule they innovate according to. Nonetheless government policy generally accommodates national interests so when the regulation is too stringent for the technology at the expected implementation date, it may get delayed to allow for technology to reach that level. This occurred in the US during their initial introduction of emissions regulations. The announced implementation date of 1975 was delayed and instead introduced progressively since the technology was not available at the time. Similarly, European Council Directives specifically mention that they have taken into account available technologies:

"Whereas the work undertaken by the Commission in that sphere has shown that the Community has available, or is currently perfecting, technologies which allow a drastic reduction of the limit values in question for all engine sizes" - Directive 91/441/EEC, amending 70/220/EEC

Another reason for regulation delay is delay of available resources, namely fuel availability. Brazil for instance, had to delay their passenger car diesel regulations in 2009 due to lack of available 50ppm fuel. We do not track fuel regulations as, to the best of our knowledge, their main impact is on the final implementation date of vehicle emissions regulations. The relevant technologies for fuels have little overlap with the technologies in emissions control. Of consequence however, may be regulations on fuel economy (CO_2 levels). The US began its Corporate Average Fuel Economy (CAFE) standards in 1975 requiring car manufacturers to reach 27.5 miles per gallon (average mpg) for passenger cars (PCs) by 1985. They were then tightened to 35.5 mpg in 2007 to be achieved in 2016 and in 2011 the new target was set to 54.5 mpg for implementation in 2025. In the EU, fuel economy standards began later but once introduced were more stringent than the US standards at the time. It was announced in 1998 that CO_2 emissions were to be reduced by 25% by 2008. Fuel economy standards target the general functioning of the vehicle and therefore may overlap with technologies we identify for emissions of other greenhouse gases.

As discussed later in our analysis, we include some robustness checks on specific technologies, namely end-of-pipe technologies such as catalytic converters, that are theoretically unaffected by fuel economy regulations.

Figure 1 below illustrates the regulation specific (estimated) market size changes over time.[4] We clearly see two cycles in the lifetime of each regulation. The early regulatory movers make up the first cycle during which the market size increases globally until some countries in that set move on to a higher regulatory level. This causes a large drop in market size for the previous regulation and a comparable increase in the new regulation. Overtime however, laggard countries will continue to adopt the older regulation and this causes another cycle for this regulation. Appendix D provides more details of this data collection process.

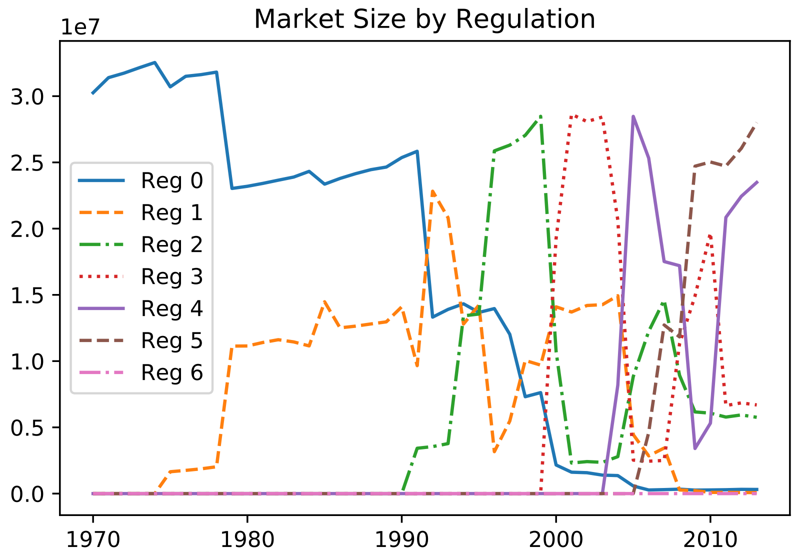

Figure 1: Market size dynamics over time where market size is measured as volume of passenger car sales.

[4]The market size is calculated using imputed sales which are described further in section 3 and the appendix.

2.2 Patent Data

Our measures of innovation are built from PATSTAT (spring 2017 version), a database on patent documents maintained by the European Patent Office (EPO). There are over 100 countries and regions covered in the database with an application filing year going as far back as the mid 1800s. This database covers essentially the population of European patents and contains very comprehensive coverage of many other countries.

Proper use of the database requires in depth knowledge of each country's policies and idiosyncrasies as well as their changes over time.[5] The database consists of one table on patent application filings containing information on filing dates, authenticator office, number of applicants, number of inventors, patent family size, priority patent identifier, application type, corresponding publication id, granted status, etc.. There is similarly a table on patent publications including information on the patent authenticator, the publication kind, the publication date, whether the publication was granted, the publication claims, and more. In addition, there is a table on people, either applicants or inventors, and their name, address details and estimated sectors. Finally, there are the tables that connect the applications and publications to people, the publications with other publications and application filings by citation, and the application filings to their priority filing. There are also smaller tables that add very specific information such as the text of abstracts, patent family citations, legal events, technology codes (IPC, CPC), product codes (NACE2), and some information on the non-patent literature collected through citations information.

We restrict our dataset to $1970 - 2013$ because 1970 is the year we first observe regulatory discussions while 2013 is chosen to avoid issues with substantial lags in data collection from different patent offices. All of the final countries in our regulatory dataset have some patent data up until 2015 however data completeness is not guaranteed and thus we use 2013 to leave a buffer.

[5]For example, the Japan Patent Office imposes an additional fee on each claim after the first. Therefore on average, Japanese patents have a lower number of claims. Number of claims have been suggested as a patent quality indicator as they define the boundaries of the technology covered in the patent. However due to issues such as country specific rules, we will not use it as an indicator.

The buffer is also important in our quality measure built from citations as they are subject to truncation. Studies have shown that most of a patent's citations are made in the first five to seven years after publication however some continue to accumulate citations afterwards.

In order to evaluate the effect of emissions regulations on innovation, we need to identify the relevant technologies. Using the table on International Patent Classification (IPC) technology codes we identify the relevant emissions control technologies and aggregate them into the categories: integrated technologies, end-of-pipe technologies, general emissions control technologies, and zero-emission vehicles technologies (see Hascic et al (2008)[8], Volleberg (2010)[16], and Aghion et al. (2016)[1] for more details). Our baseline measure will be the general emissions control technologies which consist of end-of-pipe and integrated technologies. In theory, this is the set of technologies directly impacted by regulatory change. We do not include zero emission technologies as we expect them to react differently. Our assumption of standard specific technologies is perhaps most relevant for end-of-pipe technologies as these are add-on components that directly target pollutants. Integrated technologies include fuel injection technologies, airfuel ratio sensors, crankcase technologies, exhaust gas re-circulation technologies, and ignition timing technologies. The specific IPC codes are listed in Appendix A.

Since firm-country specific market size data is unavailable, we follow Aghion et a. (.) to construct a proxy for market size from patent data. In particular we assume that the share of vehicle patents that a firm files in a country is proportional to the market share of that firm in that country. As such, we estimate the share of a firm's market in a given country from its patent applications then multiply by that country's total vehicle sales. We then aggregate over the countries in each regulatory level to get firm-regulation specific market size estimates. We identify vehicle patents by the technology field number 32 provided in Patstat.

In our final dataset we restrict to firms that have patented at least five times over our time period. This gives us a total of 2868 firms with headquarters in 48 countries.

One of the principle issues for use of patents as an innovation indicator is the measurement of quality. A naive first measure would be the count of the number of patents. However patents can be very heterogeneous in terms of innovative content. Furthermore, there may be discrepancies between countries on requirements of novelty, etc. and this may also change over time. There have been many studies on patent quality but a consensus has not yet emerged. Traditionally, an indicator of quality were triadic patents (patents with applications in the United States, Europe and Japan), nowadays it is more common to include China and South Korea in this measure as well. However, either way, it is not the ideal measure for our purposes as it would over weigh our innovation measure towards those markets. Instead, a simple way to measure quality is to only count patents that have made applications in more than one country.

Since there can be substantial application, legal and possibly translation fees associated with each patent application, the decision to make a patent application must mean the expected payoff is higher than the costs.[6] Patents with applications in multiple countries are both an indicator of high quality as well as an indicator that the applicants are connected with multiple markets. It is obvious that applicants with activity in more than one market are the most likely to be affected by the relative timing of regulations. We therefore expect this high quality indicator to be more reactive than a simple count of all patents. Therefore, this is both an indicator of quality as well as a good selection of technologies that are most affected by the timing of regulation implementation.

Another common measure for patent quality is a value assigned based on forward citations. This implies that a patent cited ten times is worth more than a patent cited once. Jaffe and Trajtenberg (2017)[10] conduct a good survey of the current methods in this respect. One takeaway is that the citing patents should themselves have a value and that it should be taken into account when valuing the cited patent. The ideal method would be to take into account the entire history of citations however this is not tractable given our resources and therefore we use a second

[6]Strategic use of patents, such as patent boxes and patent off-shoring for tax purposes, are becoming more and more common in recent years but arguably still a small part of the entire patent system. Here, we will assume only traditional use of patents.

order measure where we multiply the citing patents' value by a discount factor and add it to the nominal number of citations a patent has received. We still however have to interpret this measure with caution. Propensity to cite may have changed over time and different countries have different requirements for citations of prior art.

When calculating a value of firm innovation we can further improve upon this measure by dividing by the number of patent applicants. Commonly done in the literature, this is a better measure of the value of a patent to the firm as the applicants will split the benefits of the patent. To do this we simply divide by the number of applicants provided by PATSTAT.

For the next step of our analysis we merge patents to firms. Although PATSTAT provides a link between applicant and patent application, there is no structured procedure for noting applicant names. A single applicant may change the spelling of their name in different applications and in different patent offices. As such, simply using the PATSTAT applicant-patent application link table will result in much too many observations. There have been a number of attempts to harmonize the names in PATSTAT however they are subject to errors and although substantially cleaner, still encounter the same problem. To deal with this, we will use the firm-patent association dataset available in Orbis. Orbis is maintained by Burean Van Dijk and firms have a clear identifier with the associated patent application. Since Orbis includes firm financial measures, this will also allow us to merge with the financial information of the firm later on.

Patent applications can be filed in their respective national offices or in certain regional offices. The Patent Cooperation Treaty (PCT), signed in 1970, was designed to facilitate patent protection internationally. Similarly, Europe developed the European Patent Convention *"to strengthen co-operation between the States of Europe in respect of the protection of inventions"* in 1973. It established a system of law in Europe, for the 38 contracting states at the time, to allow a single procedure for the grant of patents that are ultimately subject to the same conditions as a national patent granted by that State.

In particular the EPO has an EP patent that can apply to all member states provided the applicant has paid the post grant fee in those states. As we are interested in the number of patents a firm holds at the country level, we infer the countries covered in an EP patent with the post grant fees. PATSTAT provides a legal event dataset that tracks changes made to a patent however this dataset is incomplete and, by construction, only covers the applications that have been granted. In order to assign a country to each EP patent application, we first use the legal event table to identify countries that received post grant fees. To be specific the legal event codes used were 'PGFP' (Post grant: annual fees paid to national office), 'AKX'(Payment of designated fees), 'AK' (Designated contracting states), and 'RBV' (Correction of designated states). If a patent application has an RBV correction, we use only those states. For the patent applications with no national information, we generate an estimate from the applicant history. To do so, we take the outer set of the countries listed in PGFP, AKX, and AK and we assign each country a fractional weight of $\{\text{number of patents per firm}\}^{-1}$ to get a firm distribution for each applicant. We then average these distributions over the set of applicants. If the EP patent does not have any applicant information, we assign estimated designated states and a corresponding probability from the year average.

Patstat contains data on different types of intellectual property. The EPO has categorized this into three categories: PI (patents for invention), UM (utility models), and DP (design patents). In our analysis we restrict to only the first category of patents. Utility models were designed to be a weaker form of intellectual property rights. The innovative requirement is less stringent and it is usually smaller firms that hold utility model patents. Since there are already issues with measuring patent quality, we decide to exclude these patents. Design patents are evidently less relevant for vehicle emission technologies and are excluded as well.

Figure 2 below provides a look at the share of emissions control patents and zero emission vehicle patents over all vehicle patents. Notably our definition of zero emission vehicle (ZEV) patents is quite broad and therefore makes up a relatively large share on this graph. Nonetheless we see that the share of ZEV patents has increased substantially in recent years. The total number of vehicle patents, and in general all patenting activity, has also increased substantially in recent years.

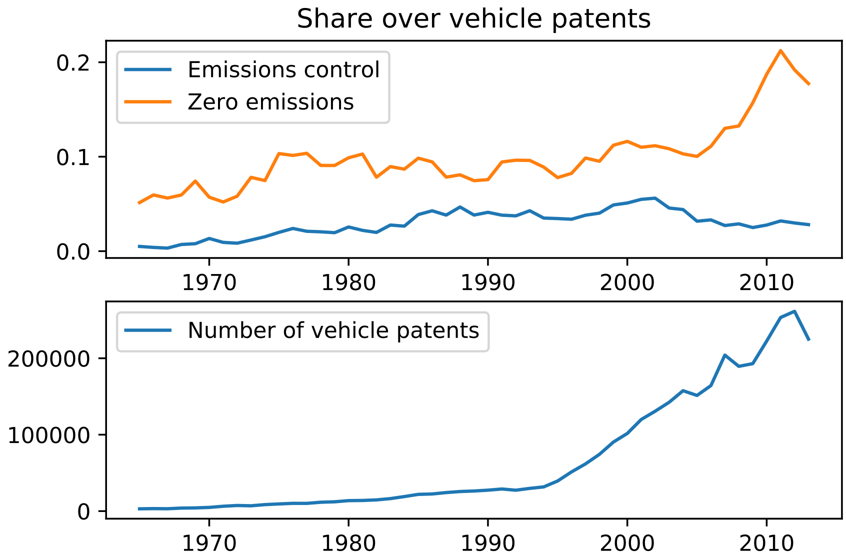

Figure 2: The top figure displays the share of emissions control patents and zero emission technology patents over all vehicle patents. The bottom figure displays the level of vehicle patents over time.

Figure 3 displays the share of catalytic converter patents in emission control patents over time. We can see a few waves of patenting with one in the early 1970s then the 1990s and now in the late 2000s.

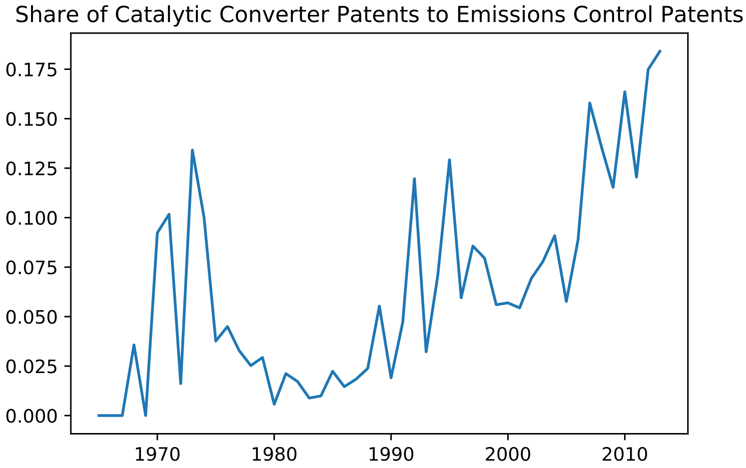

Figure 3: Share of catalytic converter patents in emission control patents

3 Empirical Model

Our baseline firm-level specification for firm i in year t is the following poisson regression:

$$P_{i,t}^{EC} = \sum_{r \in \mathbb{R}\mathrm{eg}} \alpha^r \cdot Mkt_{i,t-1}^r + \sum_{r \in \mathbb{R}\mathrm{eg}} \beta^r \cdot Mkt_{i,t-1}^r * Timing_t^r + \gamma \cdot S_{i,t-1}^{EC} + \boldsymbol{\theta} \cdot \boldsymbol{X_{i,t}} + \epsilon_{i,t} \quad (1)$$

Where $P_{i,t}^{EC}$ is our innovation measure built from patent applications on emissions control technologies as described above. $Mkt_{i,t-1}^r$, for each $r \in \mathbb{R}\mathrm{eg} \equiv \{1,2,3,4,5\}$, is logged regulation specific market size measure; $Timing_t^r$ is a regulatory timing term; $X_{i,t}$ are the controls including firm and year fixed effects and, since we log many of our explanatory variables, dummy variables for zeros in the various log variables. Finally, $S_{i,t-1}^{EC}$ is the emissions control technology log knowledge stock. [7]

The $Timing_t^r$ variable is a measure of early/late mover. Our primary measure of choice is $Order_t$.[8] It is defined as a set of variables $\{Order_t^1, Order_t^2, Order_t^3, Order_t^4, Order_t^5\}$ that

[7] We proxy for $S_{i,t-1}^{EC}$ with patent stock calculated from the traditional inventory method with a 15% discount rate ($\rho = 0.15$). To be precise:

$$S_{i,t}^{EC} = P_{i,t}^{EC} + (1-\rho) * S_{i,t-1}^{EC} \quad (2)$$

[8] Instead of using a dummy variable to define leader and follower we use $Order_t$, a variable in $\mathbb{N}^+$. This

track the years as countries adopt the corresponding regulations. Each $Order_t^r$ is a time varying variable specific to each regulation r. In 1970, the first year of our data, $Order_t^r$ is equal to 0 since no countries have adopted any regulations yet. It is assigned 1, 2, 3, etc. as the regulation gets implemented by different countries over time. For example, $Order_t^1$ is equal to 0 until 1975 when Japan implements EU 1 equivalent standards and 1 is assigned. It remains one until 1979 when the US reaches approximately Euro 1 equivalent levels and is assigned 2. It is then assigned 3 in 1985 when the Stockholm agreement was signed by certain European countries as well as the US and Canada.[9] The next time it changes is when the European Union uniformly adopts vehicle emission regulations in 1992, officially defining the Euro 1 level... and so on. $Order_t^2, Order_t^3, Order_t^4, Order_t^5$, etc. are defined similarly with their own timelines. This variable captures both a temporal distance as well as information on regulatory changes.

To be precise, we construct this variable by first defining an intermediate $Change_{c,t}^r$ variable:

$$Change_{c,t}^r = \mathbb{1}\{r_{c,t} > r_{c,t-1}\} \tag{3}$$

Next the variable is simply:

$$Order_t^r = Order_{t-1}^r + \max_{c \in \mathbb{C}}\{Change_{c,t}^r\} \tag{4}$$

with $Order_0^r = 0 \ \forall r \in \{1, 2, 3, 4, 5\}$. Notably, this variable captures the global situation in terms of regulation adoption and is therefore not firm specific.

Our baseline specification captures both the push and pull effects of innovation creation typically described in the literature. An expanding market size makes up the demand pull effect while previous build up of knowledge and patent stock facilitates new inventions and therefore 'pushes'

allows us to better evaluate early and late mover specific to each regulation. For example, the US and Japan were early movers on the regulatory scene however they developed diverging regulatory procedures. Europe, although slower to adopt vehicle emission regulations, developed a regulation framework that more countries were willing to adopt. Therefore, in a sense, they were an early mover as well. Using a fixed definition of regulatory leader may miss these subtleties.

[9] Prior to EU 1, there were some European countries that had aligned with the US limit levels in 1985 in what is known as the Stockholm agreement. However they switched to the Euro scheme once it was established.

innovation forward. In addition, our specification disentangles the market size effect from the regulation timing effect by introducing an interaction term of market size and timing. Regulation timing adds a temporal dimension to our study and addresses the question of whether there are disproportional benefits to being an early mover. We include all five regulatory levels separately because each regulatory level has its own idiosyncrasies, they do not necessarily increase at the same pace nor by equal degrees of stringency.

To avoid endogeneity issues, we would ideally take presample patent data and build constant weights for each firm. However this would require the strong assumption that firm shares have not changed over our sample period. Since our analysis covers years 1970 to 2013, a period of over 40 years, this assumption is too strong. Instead we use two methods to build firm shares. In our baseline we fix ten year intervals and build the firm shares from average patenting in the previous ten year period. This is updated every ten years and allows us to interpret coefficient estimates better. However it introduces large discontinuities with the advent of each ten year interval. For an alternate measure, we smooth these discontinuities by taking the one year lagged knowledge stock firm shares instead.

To summarize,

$$Mkt^r_{i,t} = log\left[\sum_{c\in\mathbb{C}} \frac{P^{car}_{i,c,t_0}}{\sum_{l\in\mathbb{I}_c} P^{car}_{l,c,t_0}} Sales_{c,t}\mathbb{1}\{R_{c,t} = r\}\right] \tag{5}$$

where $\mathbb{C}$ is the set of all countries.[10] $\mathbb{I}_c$ is the set of firms operating in country c. $Sales_{c,t}$ are passenger car sales in country c at time t.[11] $R_{c,t}$ is the regulatory level in country c in year t and $R_{c,t} \in \{0, 1, 2, 3, 4, 5\}$. Our baseline measure P^{car}_{i,c,t_0} measure is the firm ten year average:

[10]In practice, our measure added 0.01 before taking the log in order to keep the zeros. A dummy variable is included to control for different behavior at the zeros.

[11]See Appendix C for more details on this variable. In general the sales data was collected from OICA but most countries are only covered from 2005 onwards. European countries are covered starting in 1990 and we can find some other country specific values from their respective national websites. Many values however had to be imputed and it is possible our imputed values are substantially different from actual values since our data is not randomly missing, it is a strong assumption to assume the same behavior for our whole period. For additional robustness checks, we will multiply by country population or GDP values instead of sales.

$$P^{car}_{i,c,t_0} = \frac{1}{10} \sum_{\tau=t-10}^{t-1} P^{car}_{i,c,\tau} \tag{6}$$

while our alternative method with lagged knowledge stock is simply:

$$P^{car}_{i,c,t_0} = S^{car}_{i,c,t-1} \tag{7}$$

where here we use the stock of vehicle patents built up by a firm i in country c. Note that in comparison to the emissions control stock variable in the baseline regression, this stock variable covers all vehicle patents and is disaggregated at the country level.

4 Results

Table 2 presents our core results. All columns control for firm fixed effects and include a full set of year dummies. The dependent variable in columns (1) and (3) is a simple count of emissions control patent applications filed by a given firm in a given year. Columns (2), (4), (5), (6), and (7) use a dependent variable called 'HV count' this stands for high value patent count where we identify a patent as high valued when it has been filed in at least two countries. Since each patent application process incurs substantial fees, a patent is implicitly worth more when it is filed in more countries. This also rules out some cases of patenting for strategic reasons and is a measure commonly used in the literature. Column (3) presents the results from the baseline regression. The coefficient on Regulation 1 suggests that a 10 percentage point increase in market size of regulation 1 leads to a 0.7% increase in emissions control technology patenting. The coefficient on the interaction term is weakly negative. This confirms a weak regulatory leadership effect. Our results for regulation 1, 2, and 3 are of different magnitude but are highly significant and follow the same direction. The market size effect on its own is larger and positive and the interaction term with the timing effect is negative although much smaller in magnitude than the market size coefficient. This provides evidence for decreasing returns to late regulation implementation.

Results for Regulations 4 and 5 however are more ambiguous. The coefficients are largely insignificant and seem to be in the opposite direction. This may reflect the increase in more 'soft' inventions. Namely innovations in software that are not well captured in patent data. Furthermore, our identification of emissions control patents is not perfect and could be missing information for more recent years. Our main technology identification was constructed following Hascic, de Vries, and Johnstone [8] which was published in 2008. In 2008, Euro 4 had just passed the peak of its first cycle and Euro 5 had just started. As it has been suggested that emissions control technology is standard specific, there may simply not be enough data to evaluate and identify the dominant technologies for Euro 4 and Euro 5[12]. The coefficients on Euro 5 can essentially be treated as controls as restricting the dataset to $\leq$ 2013 means we do not capture the entire life cycle of Euro 5 (See Figure 1 - we are not in the second peak region yet).

Another possibility is the impact of what we now know as cheating scandals among some large car manufacturers in the more recent years. Although these scandals have been largely focused on diesel engines, and we use petrol regulations, there are potential technology spillovers since we are not able to perfectly separate the two in our dependent variable. The coefficient may be decreasing in market size since, all else equal, certain firms had found increasingly over time that they could get away with manipulating the driving tests in large markets. However we expect that this effect should be small since it only covers a handful of firms while we have thousands of firms in our dataset, however there could also have been cascading effects if assembly firms decreased their demand for these technologies from smaller more specialized firms.

Table 2 shows that our results are fairly stable for regulations 1, 2, and 3. The coefficient varies with a maximum of 0.03 degrees for market size and 0.005 degrees on the interaction term. The coefficients on the regulation 2 variables are particularly stable. Using high value patents as our innovation indicator generally brings down the market size coefficient on regulations 1 and 2 while it increases for the other regulations although not to a significant degree. We also test with

[12]See Lee and Berente (2013)[11] on dominant technologies

an additional vehicle patent stock measure to account for general firm propensity to patent and potential knowledge spillovers. Columns (1) and (2) do not include any patent stock measures in the explanatory variable. To be accurate, including the emissions control patent stock does not meet the strong exogeneity condition we need for our poisson regression.[13] Columns (1) and (2) therefore do not use a knowledge stock variable and the results are still relatively similar. We will always report the results from both a regression with knowledge stock explanatory variables and the results without.

Columns (6) and (7) are comparable with columns (3) and (5) except we use a different discount rate of 20% to compute the patent stock. The coefficients are very similar so this confirms that our results are robust to different discount rates and the construction of our patent stock variable.

We also see that the coefficient on the emissions control patent stock and high value stock variables are positive. This is what we expect to see in terms of a "technology push" effect. When we add the firms' vehicle high value patent stock, the coefficient on emissions control stock is still positive but is no longer significant. The vehicle patent stock coefficient is slightly negative albeit not significant at all. This might hint at a redirection of research and development efforts within the firm towards emissions control patents in contrast to an expansion of total effort.

[13]See Blundell et al. (1999)[5]

	(1) Count	(2) HV count	(3) Count	(4) HV count	(5) HV count	(6) HV count	(7) HV count
Reg 1 Market Size	0.0920***	0.0877***	0.0772***	0.0672**	0.0602**	0.0687**	0.0619**
	(0.0235)	(0.0265)	(0.0219)	(0.0267)	(0.0267)	(0.0267)	(0.0266)
Reg 2 Market Size	0.0537***	0.0456***	0.0596***	0.0513***	0.0519***	0.0513***	0.0518***
	(0.0158)	(0.0173)	(0.0163)	(0.0175)	(0.0175)	(0.0174)	(0.0174)
Reg 3 Market Size	0.0756***	0.0796***	0.0562***	0.0668***	0.0673***	0.0625***	0.0630***
	(0.0203)	(0.0179)	(0.0182)	(0.0193)	(0.0196)	(0.0194)	(0.0198)
Reg 4 Market Size	0.0224	0.0254	-0.0007	0.0102	0.0146	0.0083	0.0124
	(0.0178)	(0.0193)	(0.0181)	(0.0193)	(0.0185)	(0.0191)	(0.0182)
Reg 5 Market Size	-0.0270	-0.0184	-0.0392*	-0.0248	-0.0243	-0.0259	-0.0254
	(0.0239)	(0.0259)	(0.0221)	(0.0248)	(0.0249)	(0.0248)	(0.0248)
Reg 1 Order * Reg 1	-0.0088***	-0.0079***	-0.0051***	-0.0044***	-0.0034**	-0.0045***	-0.0035**
Market Size	(0.0014)	(0.0016)	(0.0014)	(0.0016)	(0.0016)	(0.0016)	(0.0016)
Reg 2 Order * Reg 2	-0.0033***	-0.0034***	-0.0024***	-0.0026***	-0.0025***	-0.0025***	-0.0024**
Market Size	(0.0009)	(0.0011)	(0.0009)	(0.0010)	(0.0010)	(0.001)	(0.0010)
Reg 3 Order * Reg 3	-0.0028**	-0.0042***	-0.0033**	-0.0042***	-0.0040**	-0.0041***	-0.0039**
Market Size	(0.0013)	(0.0014)	(0.0013)	(0.0014)	(0.0016)	(0.0014)	(0.0016)
Reg 4 Order * Reg 4	0.0004	0.0005	0.0009	0.0009	0.0010	0.0009	0.0010
Market Size	(0.0022)	(0.0024)	(0.0021)	(0.0024)	(0.0024)	(0.0024)	(0.0024)
Reg 5 Order * Reg 5	-0.0025	-0.0013	-0.0002	0.0001	0.0013	0.0002	0.0013
Market Size	(0.0037)	(0.0042)	(0.0035)	(0.0040)	(0.0041)	(0.0040)	(0.0040)
Emissions control stock			2.938E-5***				
at 15% discounting			(8.97E-6)				
Emissions control HV stock				1.968E-5**	2.370E-5		
at 15% discounting				(9.58E-6)	(1.791E-5)		
Vehicle HV stock					-3.81E-6		
at 15% discounting					(1.074E-5)		
Emissions control HV stock						2.776E-5**	3.059E-5
at 20% discounting						(1.386E-5)	(2.321E-5)
Vehicle HV stock at							-2.79E-6
at 20% discounting							(1.201E-5)
Total observations	120314	103931	120314	103931	103931	103931	103931

Table 2: Baseline Regressions: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs with a 0.01 added beforehand to avoid losing all observations with any zeros. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. Our data is a balance panel from 1970 to 2013 as we unfortunately do not have entry and exit information and therefore simply assume zeros for years with no patenting data. All explanatory variables are lagged one year.

4.1 Robustness checks

Table 3 provides a robustness check using the second method for the firm market share proxy in the market size variable construction. Using lagged patent stock smooths the discontinuity of ten year fixed intervals. The results are similar in that coefficients on regulations 1, 2, and 3 are positive and significant on market size and negative, of smaller magnitude, and significant on the interaction term with $Order_t^r$. In comparison to Table 2, the coefficients on market size have a higher magnitude while the coefficients are of similar magnitude on the timing interaction term. Columns (5) and (6) include another check using log of the patent stock variables. In this case the coefficients are smaller in magnitude but we still see some significance on the market size coefficients. In general, taking the log of patent stock causes a problem with the zeros. As discussed in Hausmann, Hall, and Griliches (1984)[9]. We therefore use stock variables without a log in the remaining analysis.

	(1) Count	(2) HV count	(3) Count	(4) HV count	(5) Count	(6) HV count	(7) HV count
Reg 1 Market Size	0.1631***	0.1414***	0.1370***	0.1129***	0.0518***	0.0407**	0.1136***
	(0.0239)	(0.0266)	(0.0202)	(0.0253)	(0.0161)	(0.0199)	(0.0251)
Reg 2 Market Size	0.1351***	0.1161***	0.1347***	0.1155***	0.0572***	0.0494***	0.1161***
	(0.0211)	(0.0234)	(0.0201)	(0.0223)	(0.0172)	(0.0173)	(0.0223)
Reg 3 Market Size	0.1043***	0.0943***	0.0774***	0.0772***	0.0475**	0.0431**	0.0741***
	(0.0205)	(0.0203)	(0.0203)	(0.0217)	(0.0193)	(0.0193)	(0.0220)
Reg 4 Market Size	0.0363	0.0312	0.0034	0.0084	0.0034	0.0043	0.0068
	(0.0226)	(0.0221)	(0.0219)	(0.0236)	(0.0218)	(0.0223)	(0.0237)
Reg 5 Market Size	-0.0339	-0.0257	-0.0429*	-0.0297	-0.0232	-0.0280	-0.0302
	(0.0240)	(0.0247)	(0.0244)	(0.0254)	(0.0228)	(0.0249)	(0.0257)
Reg 1 Order * Reg 1	-0.0089***	-0.0069***	-0.0049***	-0.0033**	-0.0012	-0.0011	-0.0033**
Market Size	(0.0011)	(0.0014)	(0.0011)	(0.0014)	(0.0009)	(0.0012)	(0.0014)
Reg 2 Order * Reg 2	-0.0030***	-0.0025***	-0.0019**	-0.0016*	-0.0005	-0.0007	-0.0016*
Market Size	(0.0008)	(0.0009)	(0.0008)	(0.0009)	(0.0007)	(0.0007)	(0.0009)
Reg 3 Order * Reg 3	-0.0036***	-0.0034***	-0.0032***	-0.0029**	-0.0012	-0.0010	-0.0028**
Market Size	(0.0011)	(0.0012)	(0.0011)	(0.0012)	(0.0008)	(0.0009)	(0.0012)
Reg 4 Order * Reg 4	-0.0017	-0.0023	-0.0004	-0.0010	0.0006	-8.123E-5	-0.0010
Market Size	(0.0020)	(0.0022)	(0.0020)	(0.0022)	(0.0017)	(0.0020)	(0.0022)
Reg 5 Order * Reg 5	0.0074**	0.0085***	0.0070**	0.0078***	0.0032	0.0038	0.0078***
Market Size	(0.0030)	(0.0030)	(0.0028)	(0.0029)	(0.0025)	(0.0027)	(0.0029)
Emissions control stock			2.628E-5***				
at 15% discounting			(8.0E-6)				
Emissions control HV stock				1.682E-5*			
at 15% discounting				(9.15E-6)			
Vehicle HV stock							2.337E-5*
at 15% discounting							(1.305E-5)
log emissions control stock					0.4535***		
at 15% discounting					(0.0231)		
log emissions control HV stock						0.4531***	
at 15% discounting						(0.0253)	
Total observations	119669	103286	119669	103286	119669	103286	103286

Table 3: Robustness check on firm share in market size variable construction: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

Since the $Order_t^r$ variable is a bit unconventional, we also conduct a robustness check on a more conventional variable that we call time distance. For each regulatory level, it is constructed as a count of the years since the first implementation of that regulation. Thus for Euro 1, $Dist_t^1$ is equal to 0 until 1975 when Japan first adopts stringent vehicle emissions regulations. In 1975

$Dist_t^1$ is assigned 1. In 1976, it is assigned 2, despite no action from other countries, in 1977 it is then assigned 3, and so on. Table 4. shows the results with distance as our timing variable in the interaction term. Again, our results are consistent with our baseline. The magnitude on the interaction term for regulation 1 is smaller (0.0043 compared to 0.0088) as we would expect since Euro 1 had a long timeline with few adoptions in the first 15 years.

	(1) Count	(2) Count	(3) HV count	(4) HV count
Reg 1 Market Size	0.1203***	0.0943***	0.0831***	0.0734**
	(0.0270)	(0.0243)	(0.0291)	(0.0289)
Reg 2 Market Size	0.0627***	0.0643***	0.0551***	0.0551***
	(0.0160)	(0.0162)	(0.0174)	(0.0175)
Reg 3 Market Size	0.0674***	0.0520***	0.0633***	0.0646***
	(0.0199)	(0.0176)	(0.0189)	(0.0191)
Reg 4 Market Size	0.0171	-0.0036	0.0074	0.0120
	(0.0181)	(0.0181)	(0.0194)	(0.0185)
Reg 5 Market Size	-0.0200	-0.0336	-0.0192	-0.0194
	(0.0239)	(0.0221)	(0.0247)	(0.0248)
Reg 1 Dist * Reg 1 Market Size	-0.0043***	-0.0025***	-0.0022***	-0.0018**
	(0.0007)	(0.0007)	(0.0008)	(0.0008)
Reg 2 Dist * Reg 2 Market Size	-0.0033***	-0.0023***	-0.0024***	-0.0023***
	(0.0008)	(0.0008)	(0.0009)	(0.0009)
Reg 3 Dist * Reg 3 Market Size	-0.0021*	-0.0027**	-0.0036***	-0.0034**
	(0.0012)	(0.0012)	(0.0013)	(0.0015)
Reg 4 Dist * Reg 4 Market Size	0.0014	0.0016	0.0015	0.0016
	(0.0022)	(0.0021)	(0.0024)	(0.0025)
Reg 5 Dist * Reg 5 Market Size	-0.0037	-0.0015	-0.0013	-0.0003
	(0.0033)	(0.0031)	(0.0035)	(0.0035)
Emissions control stock at 15% discounting		2.881E-5***		
		(8.97E-6)		
Emissions control HV stock at 15% discounting			1.915E-5**	2.270E-5
			(9.54E-6)	(1.768E-5)
Vehicle HV stock at 15% discounting				-3.34E-6
				(1.062E-5)
Total observations	120314	120314	103931	103931

Table 4: Robustness check on different timing variable 'Dist': *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

Table 5 conducts a robustness check on the use of sales in the construction of the market size variable since sales has many imputed datapoints. Columns (1), (2) and (3) replace sales with population while columns (4), (5) and (6) replace sales with country GDP. Comprehensive population data was collected from the United Nations Populations Division. For GDP, we use the expenditure-side real GDP at chained PPPs (in mil. 2011 USD) from the Penn World Tables.

GDP however is also not fully available for our set of countries and set of years. When that is the case, those datapoints are simply dropped, therefore this is a very rough robustness check. Nonetheless the results still hold with both population and GDP checks.

	(1)	(2)	(3)	(4)	(5)	(6)
		By Population			By GDP	
	Count	Count	HV count	Count	Count	HV count
Reg 1 Market Size	0.0787***	0.0731***	0.0587**	0.0856***	0.0737***	0.0536**
	(0.0230)	(0.0211)	(0.0256)	(0.0238)	(0.0222)	(0.0272)
Reg 2 Market Size	0.0416***	0.0521***	0.0429***	0.0546***	0.0622***	0.0559***
	(0.0134)	(0.0142)	(0.0151)	(0.0146)	(0.0154)	(0.0158)
Reg 3 Market Size	0.0691***	0.0474***	0.0601***	0.0777***	0.0586***	0.0702***
	(0.0199)	(0.0178)	(0.0185)	(0.0198)	(0.0179)	(0.0190)
Reg 4 Market Size	0.0231	-0.0007	0.0142	0.015	-0.0074	0.0046
	(0.0163)	(0.0167)	(0.0172)	(0.0176)	(0.017)	
Reg 5 Market Size	-0.0327	-0.0429**	-0.0267	-0.0329	-0.0459**	-0.0322
	(0.0224)	(0.0208)	(0.0234)	(0.0236)	(0.0219)	
Reg 1 Order * Reg 1	-0.0072***	-0.0043***	-0.0031**	-0.0090***	-0.0054***	-0.0037**
Market Size	(0.0010)	(0.0010)	(0.0012)	(0.0014)	(0.0014)	(0.0016)
Reg 2 Order * Reg 2	-0.0027***	-0.0020***	-0.0020***	-0.0033***	-0.0023**	-0.0024**
Market Size	(0.0008)	(0.0007)	(0.0008)	(0.0010)	(0.0010)	(0.0010)
Reg 3 Order * Reg 3	-0.0024**	-0.0024**	-0.0029**	-0.0029**	-0.0034***	-0.0040**
Market Size	(0.0011)	(0.0011)	(0.0013)	(0.0013)	(0.0013)	(0.0016)
Reg 4 Order * Reg 4	0.0001	0.0008	0.0007	0.0007	0.0011	0.0013
Market Size	(0.0017)	(0.0017)	(0.0019)	(0.0021)	(0.0021)	(0.0024)
Reg 5 Order * Reg 5	-0.0016	0.0001	0.0011	-0.0020	0.0002	0.0014
Market Size	(0.0029)	(0.0028)	(0.0031)	(0.0035)	(0.0033)	(0.0038)
Emissions control		2.923E-5***			2.988E-5***	
stock		(8.76E-6)			(9.0E-6)	
Emissions control			2.506E-5			2.448E-5
HV stock			(1.730E-5)			(1.793E-5)
Vehicle			-5.14E-6			-3.89E-6
HV stock			(1.054E-5)			(1.090E-5)
Total observations	120314	120314	103931	120314	120314	103931

Table 5: Robustness check on alternative market size meaures: population and GDP.*** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

So far, the count data model we have used are poisson regressions. These are the most commonly used in the literature however they are also subject to certain constraints. For instance, the variance must be equal to the mean in the poisson distribution. To confirm that our results are robust, we run negative binomial regressions on the baseline specification. The results are shown in Table 6 below. Although the results are more variable we still see highly significant coefficients on regulations 1, 2, and 3 and sometimes for regulations 4 and 5. There is a larger amount of variation depending on the patent stock variables used. This variation may be due to the fact that the negative binomial model for panel data is in fact not a true fixed effects model (see Allison and Waterman (2002)[3]). Nonetheless Table 6 supports our main results.

	(1) Count	(2) HV count	(3) Count	(4) HV count
Reg 1 Market Size	0.1922***	0.2406***	0.0276***	0.0569***
	(0.0070)	(0.0085)	(0.0064)	(0.0075)
Reg 2 Market Size	0.0988***	0.1136***	0.0222***	0.0388***
	(0.0082)	(0.0098)	(0.0075)	(0.0088)
Reg 3 Market Size	0.1491***	0.1639***	0.0655***	0.0698***
	(0.0095)	(0.0112)	(0.0087)	(0.0099)
Reg 4 Market Size	0.0315***	0.0823***	-0.0082	0.0227*
	(0.0109)	(0.0131)	(0.0101)	(0.0118)
Reg 5 Market Size	0.0624***	0.0945***	0.0502***	0.0528**
	(0.0125)	(0.0155)	(0.0116)	(0.0137)
Reg 1 Order * Reg 1	-0.0167***	-0.0160***	-0.0045***	-0.0058***
Market Size	(0.0004)	(0.0005)	(0.0004)	(0.0005)
Reg 2 Order * Reg 2	-0.0052***	-0.0033***	-0.0015***	-0.0004
Market Size	(0.0004)	(0.0004)	(0.0003)	(0.0004)
Reg 3 Order * Reg 3	-0.0077***	-0.0078***	-0.0024***	-0.0028***
Market Size	(0.0007)	(0.0008)	(0.0006)	(0.0008)
Reg 4 Order * Reg 4	0.0082***	-0.0003	0.0096***	0.0029**
Market Size	(0.0010)	(0.0012)	(0.0009)	(0.0012)
Reg 5 Order * Reg 5	0.0019	0.0137***	-0.0078***	-0.0006
Market Size	(0.0015)	(0.0021)	(0.0014)	(0.0020)
log emissions control			0.4025***	
stock			(0.0053)	
log emissions control				0.5492***
HV stock				(0.0070)
log Vehicle				
HV stock				
Total observations	120314	103931	120314	103931

Table 6: Robustness check with negative binomial regressions: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance. Recall that the market size variables are all in logs. There are also year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

4.2 Technology Breakdown

We have so far treated the broad category of emissions control technologies but we can also disaggregate them to better identify relevant technologies. Emissions control innovations are largely made up of integrated technologies and end of pipe technologies. Integrated technologies are part of the general functioning of the car. They include fuel injection inventions, exhaust gas recirculation, crankcase emissions control, airfuel ratio, sensors, and on board diagnostics. These are technologies that will also help the general fuel economy of the car which is, although an environmental issue, also a property demanded by consumers as it translates into less money spent on fuel. As such, integrated technologies are not only affected by vehicle emissions regulations and we would expect them to be less responsive to changes in emission regulations. End of pipe technologies mostly consist of catalytic converters. Exhaust gas re-circulation technologies can arguably be included but here we follow Hascic et al (2008) and consider them part of the integrated technologies group. End-of-pipe technologies are modular components added to the end of pipe, to treat the emissions output from the combustion process. They can be more precise in targeting a specific pollutant. Intuition suggests that these technologies should be more responsive to regulation changes.

Table 13, in the Appendix, summarizes the results when only catalytic converter patents are counted in the dependent variable. Surprisingly our results have lost some significance and the coefficient on market size for Euro 1 is completely insignificant. Since catalytic converters can target a specific pollutant, they may be more relevant for certain regulations. These results would imply that catalytic converters were not the dominant technology associated with Euro 1. Since Euro 1 was the first regulation on these vehicle emission pollutants, catalytic converter technology would have started from a knowledge stock of zero and may have taken a bit of time to develop and get established. Integrated technologies on the other hand have always been part of the car system and were perhaps easier to improve to meet Euro 1 requirements.

However if we look at figure 3 in section 2, we see that the share of catalytic converter patents to emissions control patents was actually quite high in the early years. The fact that this does not translate into our results suggests that we may be imperfectly evaluating the regulation timing. As described above, we use regulation implementation dates for our timing variable however there is sometimes a long lag between announcement dates and implementation dates. It is likely that firm innovation efforts in emissions control technology will have increased starting from the announcement date. This seems to be the case here, since the US and Japan had both announced stringent regulations in 1970 and 1971 respectively and that is when we see catalytic converters making up a large share of emissions control patents. We choose to use implementation dates for our analysis because we expect the R&D results to be most visible in our patent data then. Firms have an incentive to keep their innovations secret until they have to put it into use, at which time it could be subject to imitation hence we expect patents to mostly be filed close to the implementation date of the regulation. The share of catalytic converters increasing in the early years could also reflect a level of regulation that we do not address. Namely, Japan began vehicle emissions regulations in 1966 and the US began in 1970 but those regulations were much more relaxed and we assumed that they did not provide any technological pressure. They are therefore included in our analysis as regulation zero, but these results suggest that we may want to define another level of regulation prior to Euro 1.

Finally, since catalytic converters are an add-on component, they do not necessarily have to be developed by traditional car manufacturers. There are firms that specialize in catalytic converter technologies and they would not have existed before vehicle regulations were implemented as this is purely addressing an environmental externality. As such, our baseline ten year average built from car patent shares would essentially be zero for these firms in the first ten year period. In Table 14 (in Appendix B), columns (1) and (2) we see that indeed market shares built from lagged knowledge stock gives us positive and significant coefficients on regulation 1 market size. The effect of regulation timing however becomes insignificant. This may be due to the issues described above.

Table 15, in the Appendix, displays the results from integrated technologies. They are quite consistent with the results from the emissions control patents baseline although the effect on timing is less consistently significant and slightly lower. In contrast to catalytic converters, we see that regulation 1 remains positive and significant. Of note, the vehicle knowledge stock coefficient is positive, albeit insignificant, while the coefficient is decidedly negative and sometimes significant in all the previous regressions that included emissions control, or catalytic converter, and vehicle patent stock. This suggests that, on a whole, the introduction of regulations is redirecting research efforts towards emissions control technologies however, with integrated technologies, there appears to be a higher degree of knowledge spillovers into general vehicle patents and as a result, an expansion in both.

We also document some results on zero emission vehicle (ZEV) technologies as they are becoming increasingly relevant. ZEVs are also a way to address environmental concerns although their viability was quite uncertain until recently. We do not necessarily expect ZEVs to be affected by emission regulations in the same way - since this technology, when available, will have zero emissions, it will meet all levels of regulatory limits. Thus regulation timing issues do not necessarily have an impact. On the other hand, the demand for ZEVs depends entirely on demand from regulations since it directly addresses the environmental externality. Since this technology was initially so uncertain, the incentive to continue R&D efforts may actually be substantially affected by regulatory changes. Table 7 shows the results from market size variables constructed with ten year average patent shares. The results are largely inconclusive and insignificant. However the issue may be that the use of the lagged ten year average share assumes that those shares are constant over the interval. This worked in the case of general emissions controls and integrated technology firms but we saw that it might pose a problem for catalytic converter firms particularly in the early years. It also appears to pose a problem here for zero emission vehicle technology. The set of firms is slightly different, as it is a nascent technology, and the assumption that their market shares are constant over ten years is too restrictive. In Figure 2 we can see the rapid increase of zero emission vehicle technology shares in the last ten years.

Table 8 shows the results from zero emission vehicles (ZEV) with market size variables built from lagged knowledge stock. The results for regulations 1, 2 and 3 are consistent with our baseline results and surprisingly significant. This strong effect could be partly due to knowledge spillovers with other emissions control technologies. It could also be partly due to technology identification issues as it has been implied that many ZEV innovations are not patentable. As such, we use a relatively broad definition of ZEV patents which could be capturing other technologies as well. The precise IPC codes used are listed in Appendix A. Table 8 suggests a positive and weakly significant although robust effect of market size for regulation 5. This did not appear in any previous results and suggests a redirection of innovation towards ZEV technologies as regulations became more stringent. The effect on timing for regulation 5 is however insignificant and the effect seems to be confounded with the regulation 4 interaction term. Nevertheless this may suggest that regulations 4 and 5 were too stringent for previous emissions control innovations and firms had decided to focus much more of their R&D efforts on radical technologies such as ZEV.[14]

[14]See Bloom et al. (2017) "Are ideas getting harder to find?"[4]

	(1) Count	(2) Count	(3) HV count
Reg 1 Market Size	0.0514*	0.0106	-0.0029
	(0.0281)	(0.0272)	(0.0274)
Reg 2 Market Size	-0.0031	0.0032	-0.0206
	(0.0197)	(0.0197)	(0.0221)
Reg 3 Market Size	0.0130	0.0069	0.0004
	(0.0213)	(0.0225)	(0.0227)
Reg 4 Market Size	-0.0340	-0.0438	-0.0399
	(0.0293)	(0.0287)	(0.0320)
Reg 5 Market Size	0.0527*	0.0455*	0.0560**
	(0.0276)	(0.0260)	(0.0282)
Reg 1 Order * Reg 1	-0.0071***	-0.0028*	-0.0015
Market Size	(0.0018)	(0.0017)	(0.0018)
Reg 2 Order * Reg 2	-0.0019**	-0.0016	-0.0008
Market Size	(0.0008)	(0.0010)	(0.0012)
Reg 3 Order * Reg 3	-0.0012	-0.0014	-0.0018
Market Size	(0.0017)	(0.0018)	(0.0019)
Reg 4 Order * Reg 4	0.0049*	0.0043	0.0043
Market Size	(0.0029)	(0.0027)	(0.0031)
Reg 5 Order * Reg 5	-0.0058	-0.0050	-0.0043
Market Size	(0.0053)	(0.0047)	(0.0055)
Zero emissions vehicle		6.529E-5***	
stock at 15% discounting		(1.581E-5)	
Zero emissions vehicle HV stock			6.914E-5***
at 15% discounting			(1.994E-5)
Total observations	82818	82818	65360

Table 7: Zero Emission Vehicle Technology: Market Size variables are constructed from method 1, lagged ten year averages. *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Order as timing interaction term				Distance as timing interaction term		
	Count	HV count	Count	HV count	HV count	Count	HV count	HV count
Reg 1 Market Size	0.1660***	0.1481***	0.1165***	0.1052***	0.0985***	0.1435***	0.1252***	0.1166***
	(0.0201)	(0.0201)	(0.0197)	(0.0198)	(0.0202)	(0.0226)	(0.0229)	(0.0234)
Reg 2 Market Size	0.1093***	0.0863***	0.0984***	0.0711***	0.0699***	0.1063***	0.0783***	0.0768***
	(0.0304)	(0.0282)	(0.0280)	(0.0266)	(0.0267)	(0.0284)	(0.0274)	(0.0275)
Reg 3 Market Size	0.0920***	0.0778***	0.0802***	0.0685***	0.0667***	0.0789***	0.0672***	0.0657***
	(0.0199)	(0.0213)	(0.0199)	(0.0209)	(0.0208)	(0.0202)	(0.0210)	(0.0210)
Reg 4 Market Size	0.0341	0.0403	0.0221	0.0332	0.0318	0.025	0.0362	0.0350
	(0.0254)	(0.0246)	(0.0251)	(0.0248)	(0.0222)	(0.0248)	(0.0250)	(0.0224)
Reg 5 Market Size	0.0538**	0.0455	0.0511*	0.0498*	0.0499*	0.0498*	0.0477	0.0473
	(0.0268)	(0.0299)	(0.0270)	(0.0297)	(0.0292)	(0.0270)	(0.0300)	(0.0296)
Reg 1 Timing * Reg 1	-0.0111***	-0.0094***	-0.0063***	-0.00547***	-0.0047***	-0.0034***	-0.0028***	-0.0025***
Market Size	(0.0014)	(0.0014)	(0.0013)	(0.0014)	(0.0014)	(0.0006)	(0.0007)	(0.0007)
Reg 2 Timing * Reg 2	-0.0038***	-0.0031***	-0.0030***	-0.0023**	-0.0022**	-0.0029***	-0.0023**	-0.0022**
Market Size	(0.0009)	(0.0010)	(0.0010)	(0.0011)	(0.0011)	(0.0010)	(0.0011)	(0.0010)
Reg 3 Timing * Reg 3	-0.0051***	-0.0049***	-0.0046***	-0.0044***	-0.0042***	-0.0041***	-0.0040***	-0.0038***
Market Size	(0.0013)	(0.0013)	(0.0012)	(0.0013)	(0.0013)	(0.0011)	(0.0012)	(0.0012)
Reg 4 Timing * Reg 4	0.0044*	0.0039	0.0048**	0.0043*	0.00440*	0.0045**	0.0040	0.0041
Market Size	(0.0022)	(0.0026)	(0.0022)	(0.0026)	(0.0026)	(0.0022)	(0.0026)	(0.0026)
Reg 5 Timing * Reg 5	0.0033	0.0053	0.0026	0.0042	0.0042	0.0031	0.0045	0.0046
Market Size	(0.0038)	(0.0042)	(0.0037)	(0.0041)	(0.0042)	(0.0033)	(0.0036)	(0.0036)
Zero emissions vehicle			3.094E-5*			3.076E-5*		
stock			(1.670E-5)			(1.668E-5)		
Zero emissions vehicle				2.831E-5	2.646E-5		2.768E-5	2.579E-5
HV stock				(2.087E-5)	(2.447E-5)		(2.080E-5)	(2.459E-5)
Vehicle					7.3E-7			7.8E-7
HV stock					(1.169E-5)			(1.143E-5)
Total observations	82732	65274	82732	65274	65274	82732	65274	65274

Table 8: Zero Emission Vehicle Technology - Market Size from lagged knowledge stock: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

4.3 Stratified sample by firm size

During the description of the regulatory dataset in Section 2, we discussed the different regulation announcement and implementation dates and how they could be affected by the political economy elements. To take a look at this issue we stratify our sample by firms' total market size into 20% quantiles with the top interval broken down into 10% intervals to really separate out the largest firms. Figure 4 shows the coefficient estimates of the interaction term at these quantiles based on our baseline specification. Out of the four regulatory levels, regulations 2 to 4 display similar reactions at the various quantiles. Namely, the lowest quantiles and highest quantiles are negative and seem to be the driver of the global negative coefficient result we saw in our baseline results. The regulatory shock is sure to be exogenous for the bottom quantiles thus the fact that it is negative here supports our previous results. On the other hand, the firms in the top quantile are expected to have an influence on the regulation implementation dates. Although we also see a negative and significant coefficient here the mechanism might be different. This result might be due to strategic use of patents by the largest firms. It could indicate that these firms are stock piling their patents and keeping them internal until the implementation date of the regulation when those technologies becomes necessary. This way they minimize the time other firms may have access to their technologies. The coefficient on the firms in the medium and medium-high quantiles are quite close to zero meaning that these firms are continuously innovating regardless of the regulation timing. These are firms that are close competitors to the frontier firms and it appears that this competition effect dominates the effect of regulation timing.

The figure for regulation 1 is quite different. It shows a different shape and coefficients with larger magnitudes. The global coefficient on this interaction term is negative as seen in Table 2. In this case, it is the firms in the medium and medium-high quantiles that are driving this global negative coefficient. As opposed to the other results, the coefficient is actually positive and significant for the firms in the second lowest quantile. This means that firms with a small market size are increasing their innovation in emissions control technologies over the duration of the regulation. We posit that this is the set of firms specialized in emissions control components - most likely catalytic converters. As there was no demand for technologies specifically targeting vehicle emissions prior to regulation 1, this knowledge stock would have started at zero. Time simply had to pass in order to build a knowledge stock for these technologies which also have knowledge spillovers to the technologies used in later regulations. Thus the technology push element is likely dominating the demand pull factor here.

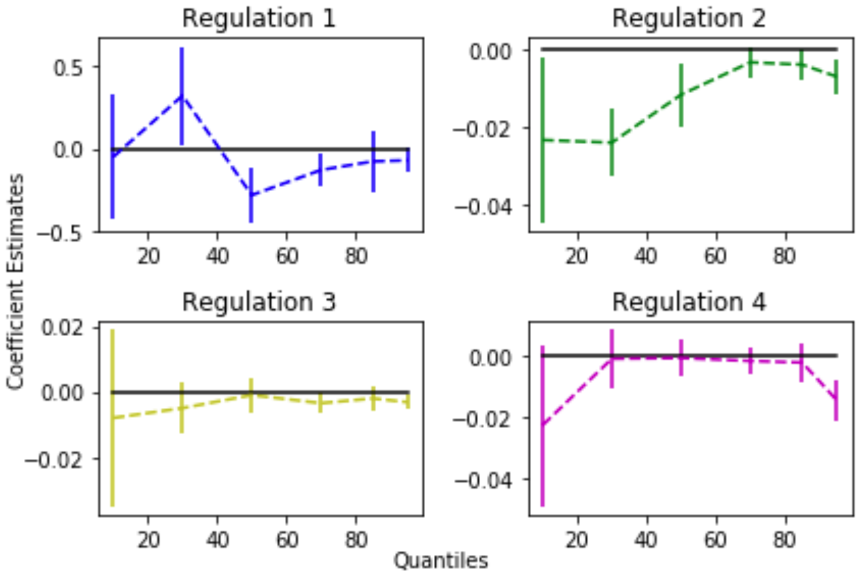

Figure 4: This figure displays the coefficient estimates on the interaction term of the baseline specification for regulations 1 to 4 by firms' market size quantiles. The bars indicate the 95% confidence interval. The market size variable uses the lagged knowledge stock proxy and the timing variable is the order measure. There are firm and year fixed effects and an emissions control knowledge stock built on the count of all patents as well. All explanatory variables are lagged one year. To be clear, the quantiles are: (0,20), (20,40), (40,60), (60,80). (80,90) and (90,100)

5 Conclusion

To put this in perspective, our study of vehicle emissions regulations strategy is also part of a wider literature on global policy strategies between countries. Here we help elucidate certain characteristics that affect global strategy games with respect to green innovation. A particularity about environmental regulations is that the direction (more stringent limits in this case) is clear at least in the short term. As there is a certain, almost unanimous, urgency worldwide to mitigate climate change. This assurance essentially removes a factor of uncertainty in firm and governmental expectations. They can expect that regulation will move in one direction and they can choose whether to be leaders or followers in this action. Being a first mover has the risk of higher short term costs as well as the potential for developing a framework too idiosyncratic for further adoption. Certain technology developments will be applicable and relevant regardless however there may be a cost to switching regulatory frameworks later on.

Our results provide evidence that there are higher innovation benefits to being a regulatory early mover. Both market size and timing effects are strongest for Euro 1 although also highly significant for regulations 2 and 3. Regulations 4 and 5 have been inconclusive however. This may be due to mis-identification of relevant technologies or a shift towards zero emission vehicle development or simply due to the cut off in those regulations life cycle. Furthermore, since a substantial part of research and development on reducing vehicle emissions has become more software related in recent years, patent data may be deteriorating as an innovation measure as software code is more likely to be kept secret and intellectual property rights are not well established for software code yet.

Our analysis leads to some interesting questions for further research. For instance, how does total innovation react to changes in these regulations? As we saw in the results, when emissions control patent stock and vehicle patent stock are both included in the regression, the coefficient on vehicle patent stock is negative - except for the case when integrated technology patents are the dependent variable. Although insignificant, it suggests that innovations in general vehicle technologies and integrated technologies are complementary. In contrast, development of end-of-pipe technologies may be redirecting R&D resources from other vehicle research sectors.

Also, how has the timing of these regulations affected firm productivity? Competitiveness? Employment? Firm entry and exit dynamics? Has it created new opportunities for small and specialized firms? Catalytic converters, as add-on components, seem to be largely developed by a different set of firms. And how have changes in market structure been affected by pre-existing market positions? If a firm is a leader in emissions control technologies maybe they have less incentive to develop zero emissions vehicle technologies. As such, they maintain their high market share for the short term but when ZEV technologies reach maturity they are left catching up. This poses the question: have regulations been too focused on incremental change instead of radical innovation?

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6 Appendix

A

Additional Figures

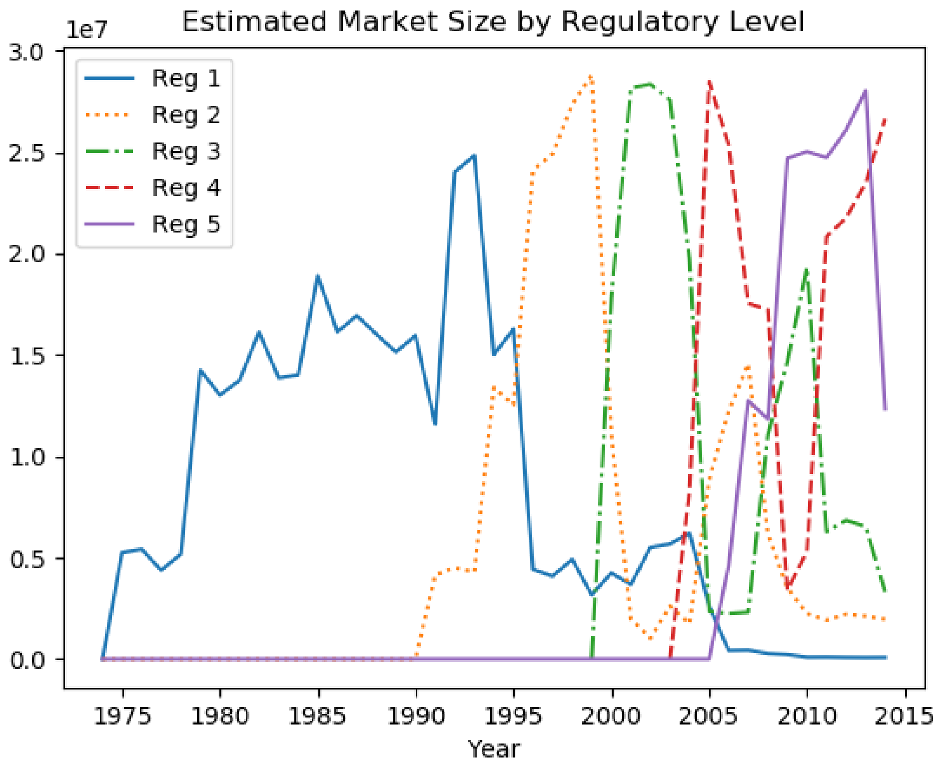

Figure 5: The estimated market size of each regulatory level over time.

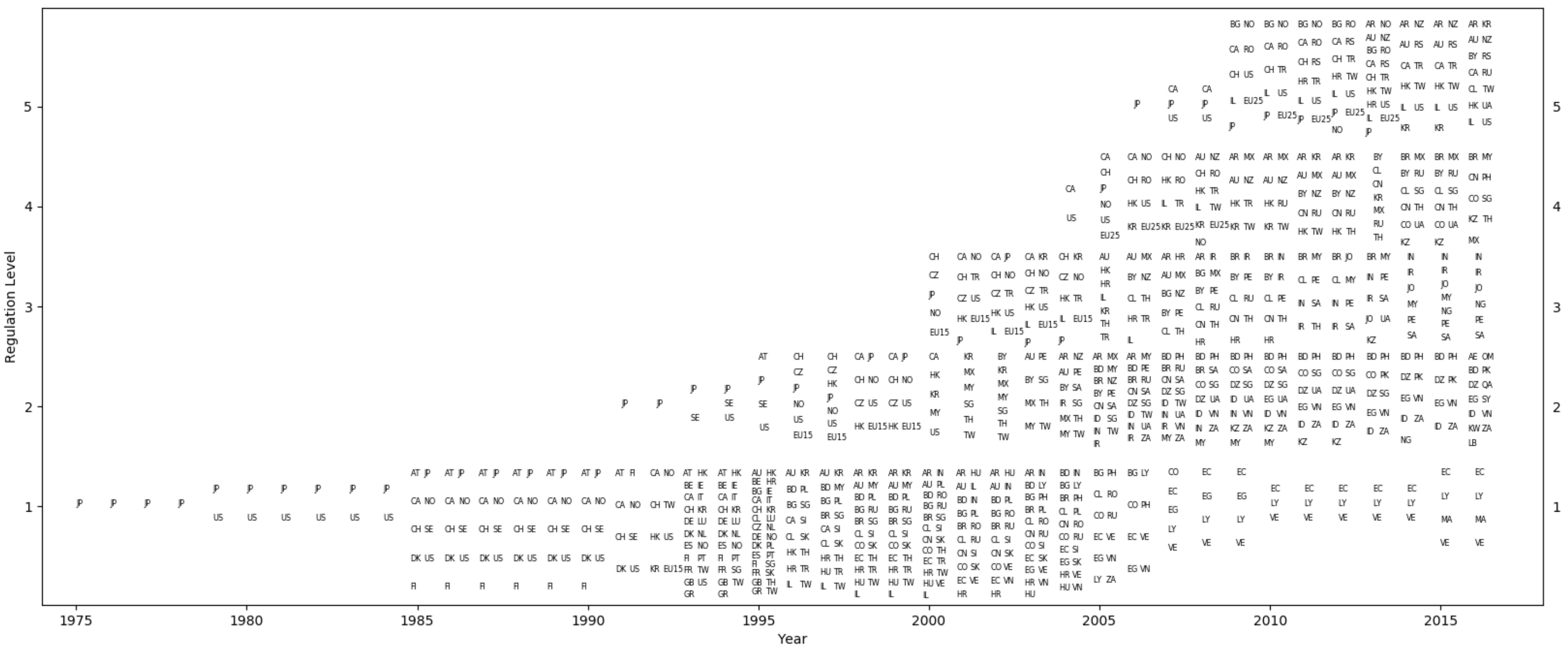

Figure 6: The implementation years of each regulatory level by country.

B

IPC Codes

Table 9: Integrated Technology IPC codes and Description

Technology	IPC Codes	Description
Airfuel ratio	F02M 67	Apparatus in which fuel injection is effected by means of high pressure gas, the gas carrying the fuel into working cylinders of the engine (e.g. air injection type) - using compressed air for low pressure fuel injection apparatus
Airfuel ratio	F02M 23, 25	Apparatus for adding secondary air to fuel-air mixtures
Airfuel ratio	F02M 3	Idling devices for carburetors (with means for facilitating idling below operational temperatures
Sensors	F01N 11	Monitoring or diagnostic devices for exhaust gas treatment apparatus
Sensors	G01M 15/10	Testing of internal combustion engines by monitoring exhaust gases
Fuel injection	F02M 39 - 63, 69, 71	Fuel-injection apparatus /Arrangements of fuel injection apparatus with respect to engines/ Pump drives adapted to such arrangements, etc.
On Board Diagnostics	F02D 41 - 45	Electrical control of supply of combustible mixture or its constituents/ Conjoint electrical control of two or more functions e.g. ignition, fuel air mixture, recirculation, supercharging, exhaust gas treatment, etc.
On Board Diagnostics	F01N 9	Electrical control of exhaust gas treating apparatus
Exhaust gas recirculation	F01N 5	Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy
Exhaust gas recirculation	F02B 47/08, 10	Methods of operating engines involving adding non-fuel substances including exhaust gas to combustion air, fuel, or fuel-air mixtures of engines.
Exhaust gas recirculation	F02D 21/06 - 10	Controlling engines characterized by their being supplied with non-fuel gas added to combustion air, such as the exhaust gas of engine, or having secondary air added to fuel-air mixture
Crankcase emissions and control	F01M 13/02, 04	Crankcase ventilating or breathing
Ignition timing	F02P 5	Advancing or retarding electric ignition spark
Fuel efficiency	B62D 35, 37/02	Vehicle bodies characterised by streamlining/ stabilising vehicle bodies without controlling suspension arrangements
Fuel efficiency	B60C 23	Devices for measuring, signalling, controlling, or distributing tyre pressure or temperature, specially adapted for mounting on vehicles
Fuel efficiency	B60G 13/14	Resilient suspensions characterised by arrangement, location, or type of vibration-dampers having dampers accumulating utilisable energy
Fuel efficiency	B60K 31	Vehicle fittings, acting on a single sub-unit only, for automatically controlling vehicle speed, i.e. preventing speed from exceeding an arbitrarily established velocity or maintaining speed at a particular velocity
Fuel efficiency	B60T 1/10	Arrangements of braking elements by utilising wheel movement for accumulating energy

Table 10: End-of-Pipe Technology codes and Description

Category	Technology	IPC Codes	Description
End of Pipe	Exhaust Apparatus	F01N 3	Exhaust or silencing apparatus having means for purifying innocuous or otherwise treating exhaust by means of air
End of Pipe	Catalytic converters	B01D 53/92, 94, 96	Catalytic converters, lean NOx catalysts, NOx absorbers, regeneration (CAT), by catalytic processes/ regeneration, reactivation or recycling of reactants
End of Pipe	Catalytic converters	B01J 23/38 - 46	Catalysts comprising metals or metal oxides or hydroxides; of noble metals' of the platinum group metals.

Table 11: Zero Emissions Vehicle Technology codes and Description

Category	Technology	IPC Codes	Description
Zero emission vehicles	Electric vehicles	B60L 11	Electric propulsion with power supplied within the vehicle
Zero emission vehicles	Electric vehicles	B60L 3	Electric devices on electrically-propelled vehicles for safety purposes; Monitoring operating variables, e.g. speed, deceleration, power consumption
Zero emission vehicles	Electric vehicles	B60L 15	Methods, circuits, or devices for controlling the traction - motor speed of electrically propelled vehicles
Zero emission vehicles	Electric vehicles	B60K 1	Arrangement or mounting of electrical propulsion units
Zero emission vehicles	Electric vehicles	B60W 10/08,24,26	Conjoint control of vehicle sub-units of different type or different function/ including control of electric propulsion units, e.g. motors or generators / including control of energy storage means / for electrical energy, e.g. batteries or capacitors
Zero emission vehicles	Hybrid vehicles	B60K 6	Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion, e.g. hybrid propulsion systems comprising electric motors and internal combustion engines
Zero emission vehicles	Hybrid vehicles	B60W 20	Control systems specially adapted for hybrid vehicles, i.e. vehicles having two or more prime movers of more than one type, e.g. electrical and internal combustion motors, all used for propulsion of the vehicle
Zero emission vehicles	Hybrid vehicles	B60L 7/1	Regenerative braking/ Dynamic electric regenerative braking
Zero emission vehicles	Hybrid vehicles	B60L 7/20	Braking by supplying regenerated power to the prime mover of vehicles comprising engine - driven generators
Zero emission vehicles	Hydrogen vehicles / fuel cells	B60W 10/28	Conjoint control of vehicle sub-units of different type or different function/ including control of fuel cells
Zero emission vehicles	Hydrogen vehicles / fuel cells	B60L 11/18	Electric propulsion with power supplied within the vehicle - using power supplied from primary cells, secondary cells, or fuel cells
Zero emission vehicles	Hydrogen vehicles / fuel cells	H01M 8	Manufacturing of fuel cells

C Tables

Below we present an additional robustness check as well as tables from the technology breakdown that were moved here to increase readability.

Our market size variable proxy is affected by the intellectual property rights and protection framework available in their respective countries. Bolatto et al. (2017)[6] posit that they are in fact the main driver of multinational firms' organization. If a country has low IP protection laws, then it is more costly for a firm to apply for a patent in that country as it increases the risk of imitation. To address this point, we use the patent protection index from Park, W.G. (2008)[12]. The index is the unweighted sum of five indicators: coverage, membership in international treaties, duration of protection, enforcement mechanisms, and restrictions. It is, however, only updated every five years. We assume the protection level is constant in the five year interval to fill in the missing years. The sales value is divided by this index when constructing the market size variable to take into account the effect of protection levels. The results are robust to this measure although the range of coefficients increase a bit. Table 12 below shows the results for both constructions by ten year average and by lagged patent stock. It also shows different combinations of patent stock explanatory variables and different dependent variables.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Market size shares built from ten year average patents				Market size shares built from lagged patent stock			
	Count	HV count	Count	HV count	Count	HV count	Count	HV count
Reg 1 Market Size	0.0986***	0.0929***	0.0811***	0.0696**	0.1684***	0.1457***	0.1401***	0.1149***
	(0.0242)	(0.0273)	(0.0225)	(0.0275)	(0.0240)	(0.0265)	(0.0202)	(0.0254)
Reg 2 Market Size	0.0585***	0.0500***	0.0631***	0.0545***	0.1380***	0.1171***	0.1363***	0.1156***
	(0.0169)	(0.0186)	(0.0169)	(0.0184)	(0.0220)	(0.0246)	(0.0209)	(0.0235)
Reg 3 Market Size	0.0834***	0.0868***	0.0612***	0.0719***	0.1142***	0.1011***	0.0827***	0.0810***
	(0.0210)	(0.0184)	(0.0191)	(0.0203)	(0.0203)	(0.0198)	(0.0202)	(0.0216)
Reg 4 Market Size	0.0231	0.0257	-0.0003	0.0101	0.0400*	0.0351	0.0047	0.0104
	(0.0187)	(0.0203)	(0.019)	(0.0203)	(0.0240)	(0.0230)	(0.0231)	(0.0246)
Reg 5 Market Size	-0.0243	-0.0166	-0.0379*	-0.0239	-0.0341	-0.0272	-0.0436*	-0.0313
	(0.0247)	(0.0266)	(0.0227)	(0.0255)	(0.0244)	(0.0251)	(0.0248)	(0.0257)
Reg 1 Order * Reg 1	-0.0096***	-0.0085***	-0.0056***	-0.0047***	-0.0099***	-0.0077***	-0.0056***	-0.0037**
Market Size	(0.0016)	(0.0017)	(0.0015)	(0.0017)	(0.0013)	(0.0015)	(0.0012)	(0.0015)
Reg 2 Order * Reg 2	-0.0038***	-0.0039***	-0.0028***	-0.0030***	-0.0035***	-0.0028***	-0.0023***	-0.0019*
Market Size	(0.0010)	(0.0012)	(0.0010)	(0.0011)	(0.0009)	(0.0010)	(0.0008)	(0.0010)
Reg 3 Order * Reg 3	-0.0030**	-0.0046***	-0.0037***	-0.0046***	-0.0043***	-0.0040***	-0.0038***	-0.0033***
Market Size	(0.0014)	(0.0015)	(0.0014)	(0.0015)	(0.0012)	(0.0013)	(0.0012)	(0.0013)
Reg 4 Order * Reg 4	0.0003	0.0004	0.0009	0.0009	-0.0022	-0.0029	-0.0007	-0.0014
Market Size	(0.0024)	(0.0027)	(0.0023)	(0.0026)	(0.0023)	(0.0025)	(0.0022)	(0.0025)
Reg 5 Order * Reg 5	-0.0032	-0.0021	-0.0005	-0.0003	0.0082**	0.0094***	0.0077**	0.0086***
Market Size	(0.0042)	(0.0047)	(0.0039)	(0.0045)	(0.0034)	(0.0034)	(0.0032)	(0.0033)
Emissions control			2.932E-5***				2.657E-5***	
stock			(9.00E-6)				(8.05E-6)	
Emissions control				1.959E-5**				1.699E-5*
HV stock				(9.62E-6)				(9.20E-6)
Total observations	120314	103931	120314	103931	119669	103286	119669	103286

Table 12: Robustness check with IP protection index weighting: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Ten year average patent share * sales				10year avg patent share * population		
	Count	HV count	Count	HV count	HV count	Count	Count	HV count
Reg 1 Market Size	0.0419	0.0372	0.0158	0.0046	-0.0111	0.0328	0.0122	0.0011
	(0.0292)	(0.0345)	(0.0245)	(0.0315)	(0.0306)	(0.0277)	(0.0229)	(0.0292)
Reg 2 Market Size	0.0613***	0.0591**	0.0611**	0.0532**	0.0524**	0.0481**	0.0521**	0.0415*
	(0.0220)	(0.0248)	(0.0237)	(0.0258)	(0.0250)	(0.0202)	(0.0221)	(0.0233)
Reg 3 Market Size	0.0774***	0.0851***	0.0565**	0.0617**	0.0683***	0.0673***	0.0455**	0.0500**
	(0.0276)	(0.0287)	(0.0249)	(0.0265)	(0.0264)	(0.0257)	(0.0229)	(0.0246)
Reg 4 Market Size	0.0322	0.0394	0.0104	0.0163	0.0302	0.0255	0.0076	0.0108
	(0.0260)	(0.0278)	(0.0247)	(0.0279)	(0.0277)	(0.0235)	(0.0241)	(0.0271)
Reg 5 Market Size	0.0065	0.0216	-0.0054	0.0105	0.0197	0.0015	-0.0111	0.0047
	(0.0284)	(0.0315)	(0.0269)	(0.0296)	(0.0308)	(0.0265)	(0.0252)	(0.0275)
Reg 1 Order * Reg 1	-0.0062***	-0.0056**	-0.0024	-0.0021	-0.0008	-0.0049***	-0.0019	-0.0017
Market Size	(0.0021)	(0.0023)	(0.0020)	(0.0023)	(0.0023)	(0.0015)	(0.0014)	(0.0017)
Reg 2 Order * Reg 2	-0.0057***	-0.0058***	-0.0040***	-0.0042***	-0.0041***	-0.0043***	-0.0031***	-0.0031***
Market Size	(0.0012)	(0.0013)	(0.0012)	(0.0013)	(0.0012)	(0.0010)	(0.0009)	(0.0010)
Reg 3 Order * Reg 3	-0.0036**	-0.0051***	-0.0034**	-0.0042**	-0.0037**	-0.0028**	-0.0024*	-0.0030**
Market Size	(0.0018)	(0.0019)	(0.0017)	(0.0018)	(0.0018)	(0.0014)	(0.0014)	(0.0015)
Reg 4 Order * Reg 4	5.68E-6	-0.0004	0.0019	0.0010	0.0013	-0.0001	0.0015	0.0008
Market Size	(0.0027)	(0.0029)	(0.0025)	(0.0028)	(0.0027)	(0.0020)	(0.0019)	(0.0020)
Reg 5 Order * Reg 5	0.0013	0.0038	-0.0002	0.0018	0.0028	0.0015	0.0003	0.0016
Market Size	(0.0046)	(0.0051)	(0.0042)	(0.0048)	(0.0049)	(0.0035)	(0.0033)	(0.0037)
Catalytic converter			0.0003***				0.0003***	
patent stock			(3.847E-5)				(3.828E-5)	
Catalytic converter				0.0003***	0.0003***			0.0003***
HV stock				(4.143E-5)	(4.845E-5)			(4.158E-5)
Vehicle					-1.636E-5**			
HV stock					(7.16E-6)			
Total observations	80797	63511	80797	63511	63511	80797	80797	63511

Table 13: Catalytic Converter Technologies: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year.

	(1) Count	(2) Count	(3) Count	(4) Count	(5) Count	(6) Count
Reg 1 Market Size	0.0776***	0.0432**	0.0758***	0.0394*	0.0965***	0.0458*
	(0.0256)	(0.0216)	(0.0263)	(0.0225)	(0.0291)	(0.0248)
Reg 2 Market Size	0.1120***	0.1012***	0.1161***	0.1040***	0.1183***	0.1025***
	(0.0310)	(0.0278)	(0.0320)	(0.0286)	(0.0321)	(0.0286)
Reg 3 Market Size	0.0593*	0.0318	0.0817***	0.0479*	0.0619**	0.0343
	(0.0314)	(0.0290)	(0.02786)	(0.0254)	(0.0311)	(0.0287)
Reg 4 Market Size	-0.0176	-0.0512*	-0.0118	-0.0489	-0.0146	-0.0489
	(0.0317)	(0.0304)	(0.0320)	(0.0305)	(0.0316)	(0.0303)
Reg 5 Market Size	-0.0306	-0.0525*	-0.0298	-0.0515*	-0.0299	-0.0544*
	(0.0330)	(0.0301)	(0.0327)	(0.0297)	(0.0332)	(0.0300)
Reg 1 Timing * Reg 1	-0.0031*	0.0004	-0.0037**	0.0002	-0.0019**	-6.02E-6
Market Size	(0.0017)	(0.0015)	(0.0018)	(0.0016)	(0.0008)	(0.0007)
Reg 2 Timing * Reg 2	-0.0010	-0.0003	-0.0014	-0.0005	-0.0012	-0.0003
Market Size	(0.0011)	(0.0011)	(0.0012)	(0.0012)	(0.0010)	(0.0010)
Reg 3 Timing * Reg 3	-0.0016	-0.0020	-0.0023	-0.0026*	-0.0015	-0.0019
Market Size	(0.0015)	(0.0014)	(0.0016)	(0.0016)	(0.0013)	(0.0013)
Reg 4 Timing * Reg 4	-0.0002	0.0016	-0.0006	0.0015	5.538E-5	0.0017
Market Size	(0.0023)	(0.0021)	(0.0026)	(0.0024)	(0.0024)	(0.0022)
Reg 5 Timing * Reg 5	0.0065*	0.0068**	0.0068*	0.0072**	0.0051	0.0056**
Market Size	(0.0036)	(0.0032)	(0.0040)	(0.0035)	(0.0032)	(0.0028)
Catalytic converters		0.0003***		0.0003***		0.0003***
stock		(3.812E-5)		(3.781E-5)		(3.827e-5)
Total observations	80410	80410	80410	80410	80410	80410

Table 14: Catalytic Converter Robustness Checks: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros.All explanatory variables are lagged one year. Columns (1) and (2) use the market size variable built from lagged patent stock * sales. Columns (3) and (4) use the market size variables from lagged knowledge stock multiplied by the IP protection index and sales. And Columns (5) and (6) use the baseline market size variables built from lagged knowledge stock times sales. Only columns (5) and (6) use time distance as the timing variable in the interaction term. All other columns use the order variable described in section 3.

	(1) Count	(2) HV count	(3) Count	(4) HV count	(5) HV count	(6) Count	(7) Count	(8) Count	(9) Count
Reg 1 Market Size	0.1044***	0.1041***	0.0866***	0.0833***	0.0768***	0.1989***	0.1686***	0.2380***	0.1939***
	(0.0259)	(0.0291)	(0.0239)	(0.0294)	(0.0288)	(0.0260)	(0.0223)	(0.0276)	(0.0242)
Reg 2 Market Size	0.0560***	0.0417**	0.0597***	0.0462**	0.0478**	0.1572***	0.1516***	0.1707***	0.1611***
	(0.0179)	(0.0203)	(0.0178)	(0.0199)	(0.0203)	(0.0223)	(0.0213)	(0.0224)	(0.0214)
Reg 3 Market Size	0.0777***	0.0784***	0.0550***	0.0657***	0.0663***	0.1305***	0.1033***	0.1223***	0.0984***
	(0.0211)	(0.0186)	(0.0196)	(0.0209)	(0.0220)	(0.0214)	(0.0219)	(0.0207)	(0.0213)
Reg 4 Market Size	0.0129	0.0133	-0.0116	-0.0005	0.0014	0.0559**	0.0263	0.0538**	0.02560
	(0.0202)	(0.0212)	(0.0201)	(0.0212)	(0.0198)	(0.0276)	(0.0260)	(0.0267)	(0.0254)
Reg 5 Market Size	-0.0381	-0.0329	-0.0488*	-0.0362	-0.0384	-0.0246	-0.0296	-0.0191	-0.0259
	(0.0284)	(0.0304)	(0.0266)	(0.0295)	(0.0292)	(0.0273)	(0.0274)	(0.0275)	(0.0276)
Reg 1 Timing * Reg 1	-0.0099***	-0.0092***	-0.0062***	-0.0059***	-0.0046***	-0.0122***	-0.0080***	-0.0061***	-0.0040***
Market Size	(0.0015)	(0.0017)	(0.0015)	(0.0017)	(0.0017)	(0.0013)	(0.0012)	(0.0006)	(0.0006)
Reg 2 Timing * Reg 2	-0.0028***	-0.0027**	-0.0019*	-0.0020*	-0.0019*	-0.0047***	-0.0035***	-0.0047***	-0.0035***
Market Size	(0.0010)	(0.0011)	(0.0010)	(0.0011)	(0.0011)	(0.0009)	(0.0008)	(0.0008)	(0.0008)
Reg 3 Timing * Reg 3	-0.0022	-0.0034**	-0.0027*	-0.0034**	-0.0036*	-0.0050***	-0.0043***	-0.0039***	-0.0035***
Market Size	(0.0014)	(0.0016)	(0.0015)	(0.0016)	(0.0020)	(0.0012)	(0.0012)	(0.0011)	(0.0011)
Reg 4 Timing * Reg 4	0.0006	0.0007	0.0013	0.0013	0.0011	-0.0022	-0.0010	-0.0016	-0.0006
Market Size	(0.0026)	(0.0028)	(0.0025)	(0.0028)	(0.0029)	(0.0025)	(0.0024)	(0.0025)	(0.0024)
Reg 5 Timing * Reg 5	-0.0056	-0.0054	-0.0033	-0.0039	-0.0026	0.0073**	0.0073**	0.0051	0.0054*
Market Size	(0.0043)	(0.0047)	(0.0041)	(0.0045)	(0.00467)	(0.0036)	(0.0033)	(0.0032)	(0.0029)
Integrated technologies			3.007E-5***				2.259E-5***		2.175E-5***
stock			(9.23E-6)				(7.04E-6)		(7.04E-6)
Integrated technologies				1.904E-5*	9.15E-6				
HV stock				(1.01E-5)	(1.744E-5)				
Vehicle HV stock					7.85E-6				
					(1.016E-5)				
Total observations	95761	78131	95761	78131	78131	95417	95417	95417	95417

Table 15: Integrated Technologies: *** denotes 1% significance; ** denotes 5% significance; * denotes 10% significance with robust standard errors in parenthesis. Recall that the market size variables are all in logs. There are also firm fixed effects, year dummies and standard dummy variables for each regulation market size and patent stock variables to control for different behavior at the zeros. All explanatory variables are lagged one year. Columns (1) to (5) are the baseline results ten year averages * sales. Columns (6) and (7) use lagged patent stock share * sales. And columns (8) and (9) use lagged patent stock shares * sales with the distance as the timing interaction term.

D Sales imputation

We imputed country passenger car sales for the construction of our market size variable. The initial data was gathered from OICA (Organisation Internationale des Constructeurs d'Automobiles) and certain country specific automobile associations that offered more extensive data, namely the American Automobile Manufacturers Association provided data as far back as 1970. OICA passenger car sales data began in 2005 and their passenger car registration data for European countries began in 1990. When sales data is unavailable, we proxy with registration data. When registration is also not available we impute the sales number from population data. The imputation is done separately for each country and their adjusted r squares are tracked. When we plot the residuals, they are fairly distributed. A couple countries, notably, China, has a lesser fit compared to the other countries. In comparison, when we regress on population, GDP, interest rate, and oil price, the explanatory variable of highest significance is GDP. The regression with both GDP and population generally provide higher r squares however the out of sample fitting sometimes give negative values. We therefore use a combination of population and GDP to impute country sales when the data is available and when the results are sensible. Otherwise we use only population data. The adjusted r squares are all above 0.80 and most are above 0.90.

Our reliable country sales data only goes back to 2005 (1990 for select countries) and sometimes even those data points are estimated. So we are arguably imposing a very strong assumption that the auto industry and consumer purchasing behavior remain the same over the years. In the robustness section we also included checks on the market size variable without multiplying by country sales and using population or GDP instead. Since our market share proxy is potentially very noisy, multiplying by imputed sales, another noisy variable, can be confounding.

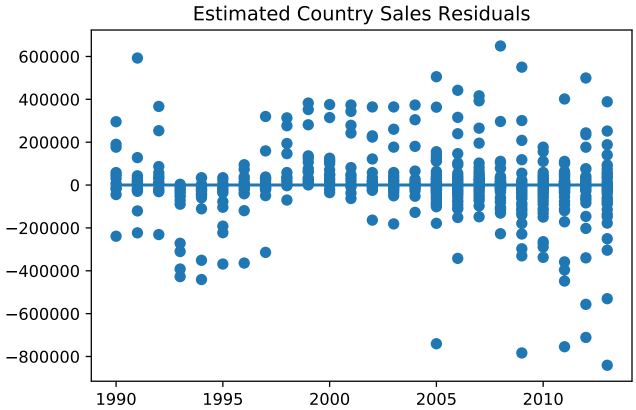

Figure 7: Estimated sales residuals: The residuals from a simple OLS run on either only population or both population and GDP data. Depending on whether the country's GDP reporting goes back to 1970 and whether the estimated sales values are reasonable. Note that residuals for China are missing from this figure.

E Regulatory Data Details

The statement on regulatory scope in the EU quoted in section 2 mentions different vehicle sizes. M1 refers to passenger vehicles with less than eight seats excluding the driver's seat. M2 and M3 generally cover buses, namely passenger vehicles with more than eight seats. N1 are vehicles used for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes. Therefore, in general Euro 1 applies to light vehicles. There is similarly a Euro regulatory system that applies to heavy duty vehicles usually denoted by roman numerals but they were adopted a bit later and we will not cover them in our analysis.

Although these categories define our baseline regulation, different countries may have their own vehicle category definitions. In collecting regulatory data we may encounter countries that have different vehicle classification methods or in some cases simply no clearly defined vehicle categories. [15] The other vehicle categories that commonly appear are Light Duty Vehicle (LDV), Light Commercial Vehicle (LCV) and Passenger Car (PC), as well as medium and heavy duty vehicles (MDV and HDV respectively). If a country uses these classifications and the corresponding regulatory levels are different, we take the passenger car regulatory level for our dataset. Of note, these category definitions are often different between countries. Passenger cars are usually a separate category from light trucks which are usually under the LCV category, all of which are often under the LDV category. However this is not a given. Some countries, such as the United States, Argentina, Indonesia, etc. include light trucks (or at least a partial set of light trucks) in their passenger car definition. Similarly, some countries include SUVs in their PC definition (such as China) while others include it in LCV (such as Australia). Furthermore the definitions may change over time, for example, part of the Light Trucks category in the Netherlands was later categorized as vans. Even the technical specifications by category are different for PCs in different countries. The maximum number of seats for PCs in the United States is twelve while

[15] For example, the vehicle categories in Canada were not clearly defined for many years and some categories had the potential to overlap. "The Canadian National Collision Database (NCDB) system defines "passenger car" as a unique class, but also identifies two other categories involving passenger vehicles—the "passenger van" and "light utility vehicle"—and these categories are inconsistently handled across the country with the boundaries between the vehicles blurred"

the maximum is ten in South Korea and nine in the EU and China. They also have different Gross Vehicle Weight (GVW) maximums - the limit being 3856 kg in the United States and 3500 kg in the EU. These discrepancies may add noise to our estimate of market size by regulation however it is not clear that it introduces any bias.

Another source of noise in our regulatory dataset is the different driving cycles (a.k.a. procedure to measure and test emissions). This is different both between countries and over time and may affect the effective stringency of a regulation. Furthermore, driving cycles follow their own timeline, sometimes use different vehicle category definitions, and do not always match the announcement nor implementation dates of emission regulations. Japan is a particular case in that they use driving cycle changes to increase the stringency of their emissions control while keeping the nominal pollutant emissions levels fixed.

The test procedure in Europe (the New European Driving Cycle - NEDC) currently specifies the starting vehicle temperature, the terrain and environmental conditions (flat road without wind, or on a roller test bench indoors), a sequence of driving speeds, and what components can be removed or turned off (such as lights, air conditioning, etc.). Of note, the NEDC does not test uphill terrain and tests the vehicle at a maximum allowed acceleration time of 15 seconds from 0-50km/h whereas acceleration time in reality is generally around 5 to 10 seconds. This test procedure was designed to simulate typical driving conditions in a busy city and although it has been criticized for unrealistic measurements, we posit that it has still had consequential impact on emissions control technology research and development incentives in firms.

Although we attempt to determine equivalences between country regulation stringency, sometimes it is technically not possible to compare them as some countries may set limits based on g/kWh or %ppm or assign a fleet average, they may not specify vehicle types, engine or fuel types, test procedures, etc. In these cases, based on the information we have for each country, we follow the regulatory changes overtime and note an increase in their regulatory level when it changes substantially. This occurred a few times in data for countries in the middle east or Africa.

Another case encountered was that due to the emergence of three main types of regulation (EU, USA, Japan), some countries later defined their emissions limits on two or more of these types of regulation. Peru is an example that offers two options - the vehicle can meet either an EU limit or a US limit. Surprisingly, Peru's two options are not equivalent in terms of international comparisons. In 2003, their passenger vehicles (GVW $\leq$ 2.5 tonnes and number of seats $\leq$ 6) options are Euro 2 or US Tier 0. Then in 2007 the Euro limit became Euro 3 whereas the US option did not change. The generally agreed equivalence for US Tier 0 is Euro 1 and US Tier 1 is generally compared with Euro 2. In these cases, we note the less stringent requirement in our dataset. Countries might use these tactics as a kind of barrier to trade. Another reason could be the grey import market. Peru imports a number of used vehicles from countries that have moved on to more stringent regulatory levels.

Grey import vehicles are new or used vehicles that are legally imported by circumventing the official manufacturers' distribution channels. In general, the grey import market is an issue that we cannot capture in our data and therefore cannot control for. It has notably been observed for Japanese exports since regulations change frequently there. Other large flows are Singapore and Thailand for diesel 4x4 vehicles and Germany for used vehicles going to Eastern Europe or West Africa. In these cases, the relevant regulation to consider are the import rules. There is a large amount of variety between import regulations. Sometimes it is the same as the type approval regulation however sometimes it is more strict or more slack, the vehicle categories are sometimes different, sometimes the only limit is on vehicle age and sometimes the import requirement is a specific component rather than a regulatory level. For example, many South American countries such as Ecuador, El Salvador, French Guyana, etc., only, or in addition, require that imported vehicles have catalytic converters.

Since the beginning of Euro 1, there have been six stages of increasingly more stringent emission levels as summarized in Table 1 in Section2 for petrol passenger cars. There are also regulations for Diesel cars that follow the Euro scheme. The pollutants targeted are the same as for petrol cars however diesel cars generally emit less CO and CO_2 but more NO_x and particulate matter. In light of the recent diesel emissions scandals we decide to focus on petrol emission regulations primarily.

F Regulatory Data Sources

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