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DRIVEN UP THE WALL? ROLE OF ENVIRONMENTAL REGULATION IN INNOVATION ALONG THE AUTOMOTIVE GLOBAL VALUE CHAIN

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Driven up the wall? Role of environmental regulation in innovation along the automotive global value chain

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Abstract

Are environmental regulations imposed on downstream firms effective in spurring innovation in clean technologies by upstream firms? We use a novel firm-level dataset of global scope to study whether environmental regulations have percolated up the automotive global value chain, and led to innovation (measured by patenting in abatement technologies) by suppliers at different levels of the chain. Using a Poisson estimation methodology, we find that suppliers worldwide have responded to increasingly stringent emission standards imposed on automobile manufacturers (also known as original equipment manufacturers, or OEMs) by undertaking more innovation in clean abatement technologies; additionally, we find that the smaller the gap between the average environmental regulation suppliers face from the OEMs, and that in the country where the firm is located, the more the firm innovates. In addition, we provide evidence of a spread of these positive effects of regulation on innovation, with suppliers at different upstream levels responding positively to the downstream standards. This paper has important policy implications for the design of environmental policy instruments to induce innovation in clean technologies by firms along the value chain.

Keywords: Environmental Regulation; Global Value Chains; Patents; Automotive Industry

JEL Codes: Q55 ; O31; Q58; F23

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1 Introduction

The global automotive industry has faced increasingly stringent environmental regulation in the past decades, which have become increasingly stricter with time. Environmental concerns are driven by the contribution of the industry to global warming, and its polluting nature: the transport industry is one of the largest consumers of energy, and burns the most petroleum. In the US, for example, transport accounted for 29% of energy consumption in 2016 (EIA, 2017). By sub-sector, road transport is the largest contributor to global warming (Fuglestvedt et al., 2008). The industry is also a significant polluter; in the US, transport accounts for over 50% of the total emissions of NO_X, over 30% of volatile organic compound emissions and over 20% of particulate matter emissions. The emissions intensity of automobiles, and the scale of the problem (given high rates of growth of population in developing countries, which is expected to further increase fuel demand for personal vehicles) poses a challenge to both policy-makers and automotive companies, especially in light of the emission targets to be met by 2020 under the Paris Agreement.

Most automotive companies (also known as original equipment manufacturers, or OEMs) are now expected to abide by environmental standards, or they risk being driven out of the market. Achieving fuel-efficiency and emissions reductions is the dual challenge facing automobile manufacturers, which urges them to make vehicles more efficient (PricewaterhouseCoopers, 2007). As consumer demand for clean vehicles has increased, and "technology-forcing" regulations have been put in place, OEMs have comprehensively overhauled their production processes, and inputs, to make them cleaner. However, it is also clear that environmental regulations have often been tough on them, with many found to cheat on emission standards.[1]

Broadly, automakers have resorted to three means of enhancing vehicle efficiency: improvements in engine technologies, improvements in other technologies, and the use of

[1] Recent media reports suggest that certain vehicle models of Mercedes-Benz, Honda, Mazda and Mitsubishi have failed these emission tests, while Volkswagen was found to install special devices on their vehicles to pass emissions tests (Carrington, 9 October 2015).

alternative fuels (PricewaterhouseCoopers, 2007). There is ample economic literature that suggests that environmental regulation has induced both clean innovation, and technology transfer in the automotive industry, thus providing evidence of the effectiveness of regulation in achieving these improvements (Aghion et al. (2016), Dechezleprêtre et al. (2015), Hascic et al. (2009), Lee et al. (2011)). In this paper, we focus on one aspect of this process which has been inadequately studied in the economics literature: namely, the percolation of these effects up the automotive global value chain. The importance of suppliers to the automotive industry can be inferred from the fact that suppliers contribute almost 75% of the total value of a vehicle produced (Klier and Rubenstein, 2008). The pivotal question then, that we seek to address in this paper, is whether these upstream actors respond to changes in environmental regulations that are imposed on the OEMs that they supply, by innovating in clean technologies.

Suppliers, especially in the automotive industry, are very close to their customers, the OEMs: often, they undertake OEM-specific investments (Asanuma, 1989), and more so in response to environmental regulation (Dyer and Chu (2000), Demeter et al. (2007)). This may reflect in greater innovative activity by upstream firms in response to downstream pressure, through what has been termed the "forced-linkage" effect (Godart and Görg, 2013), where the OEMs demand improvements in productivity (or greater innovation) from the upstream firms in response to regulations that are imposed on them, or threaten to "punish" the suppliers.[2]

We estimate the impact of automobile emission standards on patenting activities of a set of suppliers of the largest OEMs from 2000 to 2013. Our dataset combines information information on suppliers-OEM links from the ELM Analytics database with firm-level data on patents from ORBIS, and harmonised country-level data on emission standards

[2] There is some evidence to suggest, for example, that suppliers based in developing countries have responded to international pressure from the OEMs such as Ford, General Motors and Toyota to obtain ISO-14001 certification (Zhu et al., 2007).

from the International Council for Clean Transportation database.[3] The results of this paper focus on the sample of suppliers. The scope of this database is global, which makes this study one of the first of its kind. We measure innovative outcomes of the suppliers by patent activity from 2000-2013, which enables us to identify innovations in clean technologies at a disaggregated level, and allows us to correct for time-invariant characteristics at the firm-level (given the panel nature of the data). We use emission standards for CO_2 as a measure of environmental regulation in the automotive industry, using a dataset which has harmonised this information across countries that use different means of measurement, thus converting the data to a common denomination.

Using the Poisson estimation methodology, we find that suppliers have responded positively to more stringent emission standards that have been imposed on the OEMs, by innovating more. Specifically, we find that as the average emission standard decreases by 1 gram of CO_2 per kilometre, a supplier is likely to file 6.2% more patents. In addition, we find that suppliers file more patents if the gap between the average regulation that they face from the OEMs (which we denote as "OEM regulation"), and the regulation in the country where they are located in (which we denote as the "domestic country" regulation), is less (i.e. if the regulations across markets that they operate in are similar). We provide evidence that these effects have percolated up the value chain, namely that upstream firms at different levels responded to regulations imposed on the OEMs by increasing innovation. Lastly, we find heterogeneity in the responsiveness to regulation of suppliers that are located in developed countries, and those in developing countries, with the marginal effect on innovation outcomes being less for the latter than the former.

The first contribution of our study is that it is the first one (to our knowledge) which attempts to study whether firms at different levels of upstream activity respond to regulations that are imposed on the downstream firms in the automotive industry. There is

[3] The automotive supply chain is organised into "tiers": tier 1 (or tier 0.5) firms are those suppliers which are closest to the automakers, and supply directly to them. Tier 2 suppliers supply directly to the tier 1 suppliers, the tier 3 suppliers supply to the tier 2 suppliers, and so on and so forth. Using the data from ELM, we are able to identify at which level a firm supplies a particular OEM (up to tier 3).

ample literature that has looked at the productivity spillovers across firms having vertical and horizontal linkages (Javorcik (2004), Javorcik and Spatareanu (2008), Javorcik and Spatareanu (2009), Barrios et al. (2011)), and even some that has studied innovation by upstream firms (Greaker (2006), Sanyal and Ghosh (2013), Chakraborty and Chatterjee (2017)), but to our knowledge, our paper is the first to examine the percolation of these effects up the value chain.

The second contribution of this paper lies in its global scope: we use a unique dataset of the largest automotive companies and suppliers in the world. We have information on the locations of their major assembly plants of these OEMs, along with their suppliers at various levels. Geographically, our data spans the major automotive markets of the US, Germany and Japan, along with some other large markets such as France, Great Britain, and Canada. Our study especially benefits from the inclusion of suppliers in large emerging economies such as China, Mexico, Brazil and India, which enables us to add an interesting dimension to our analysis. While several studies have looked at particular aspects of the relationship between OEMs and their suppliers in specific countries (mainly in Japan (Arimura et al., 2011) and the US (Lee et al., 2011), using case-study data), ours is the first to encompass a large sample of both developed and developing countries for the analysis.

The structure of the rest of the paper is as follows. Section 2 presents a brief background on the automotive industry, and summaries the literature in the field, section 3 presents the conceptual framework along with some testable hypotheses, section 4 presents an overview of the data that we use for the analysis along with a description of our empirical approach, section 5 presents the main empirical results as well as some robustness checks, while section 6 concludes.

2 Background and Literature Review

2.1 Background on Automotive Industry and Environmental Regulations

The automotive industry is a relevant and interesting case to study the effectiveness of environmental regulation in stimulating innovation up the global value chain. The nature of the regulations that have been imposed on automakers have been of a "technology-forcing" nature, where firms were compelled to innovate in clean technologies beyond their technical capabilities (Lee et al., 2011). Moreover, it is a largely hierarchical industry[4], which renders it suitable for this analysis.

Suppliers and OEMs in the automotive industry collaborate closely in design, production and innovation. Suppliers are categorised by the level at which they supply the OEMs; tier 0.5 and tier 1 suppliers are large firms, which often co-locate with the assembly plants of the OEMs (especially to supply bulky components that are expensive to transport (Sturgeon and Van Biesebroeck, 2010). These firms not only directly supply components to the OEMs, but also coordinate production and innovation by suppliers at lower levels (the tier 2 and tier 3 firms (Dechezleprêtre et al., 2015).

The role of suppliers is integral to the entire automotive manufacture process.[5] Often, they belong to other industries such as chemicals and electronics, and thus collaborate closely with their customers both in product design, and in undertaking R&D activities and the technical processes of manufacturing (Kotabe et al. (2003); Geffen and Rothenberg (2000); Lee et al. (2011); Hall and Kerr (2003)).

There are several examples of firms, including suppliers, that have developed tech-

[4] The number of production stages in this industry, on average, is above 2.5: this index is 1 for an industry without any production stages (De Backer and Miroudot, 2014)

[5] A case-study which illustrates this is that of the "just-in-time" production system, pioneered by Toyota in the 1980's. The new production system demanded that Toyota work closely with the tier 1 suppliers to upgrade the production processes, which not only raised the costs of production (at least in the short-run), but also required that Toyota build close and long-term relationships with its suppliers (Kaplinsky, 2010).

nologies to meet emission standards.[6] The industry thus seems to have responded to pro-environment demands (by both consumers and governments) by innovating in clean technologies (Mondt (2000), Tao et al. (2010)).

While most automakers have imposed private standards on their suppliers[7], they are also expected to comply with public regulations that may focus on labor standards, safety standards or the environment (Kaplinsky, 2010). Two types of public regulations in the environmental sphere that are mandatory for new cars manufactured by OEMs are emission standards (or tailpipe exhaust standards for gases like carbon monoxide (CO), hydrocarbons (HCs), nitrogen oxides (NO_X) and particulate matter (PM)) and fuel-economy standards (which are equivalent to emission standards for carbon dioxide (CO_2)).[8]

There are significant international differences in the stringency of environmental regulations facing the automotive industry, even though there is evidence of convergence over time (Vollebergh, 2010). From the onset of these regulations in the 1960's in California, the US was a front-runner in terms of adopting the most exacting emission standards in the 70's and 80's. These standards (especially for CO_2, HC, NO_X and CO) remained relatively stable over time. Japan, on the other hand, adopted a strict set of standards after the US did, but maintained them at the same level of stringency from the beginning (Vollebergh, 2010). The EU was a laggard in terms of adopting standards, but through the successive Euro emission standards, is now second only to Japan in terms of stringency of emissions standards. Many developing countries have also adopted regulations of the type described above, but they have lagged behind, both in terms of when they adopted these

[6] The types of technologies that have been developed as regulations have progressively become stricter include variable valve timing, direct fuel injection, improved engine management systems and exhaust after-treatment systems (such as particulate filters and selective catalytic reduction technologies (SCR)) (ACEA, 2017).

[7] For instance, Ford Motors recognises suppliers who have not had any returns over a period of time, and those that have passed its annual audit. Toyota not only requires that its suppliers acquire two ISO accreditations (the ISO14001 and the ISO-TS16949), it also evaluates suppliers on detailed firm-specific metrics and criteria.(Kaplinsky, 2010)

[8] Another form of regulation which has been enforced in most countries are fuel requirement standards (such as those on lead and sulphur content). The primary price-based instrument is a tax on fuel, which may also serve the purpose of raising revenue for governments (Newbery (2005), Vollebergh (2010)).

policies, and often in the stringency of the policy itself (Perkins and Neumayer, 2012).

2.2 Literature Review

2.2.1 Role of Environmental Regulation on Economic Competitiveness

The first branch of literature in which we can place this paper is that of the the role of environmental regulation in fostering economic competitiveness. In his 1991 paper, Michael Porter highlighted the possibility that more stringent environmental regulation may in fact facilitate competitiveness, through reduction in the use of hazardous chemicals, and less generation of waste, for example (Porter, 1991).

The channel that was proposed by Porter and Van der Linde (1995) for the influence of "well-designed" regulation on competitiveness of firms was through innovation (Ambec et al., 2013). The essence of their study was that environmental regulation (if it were based on market-based instruments, or performance standards) would enhance innovative capabilities of firms, and that this may (often) supersede the costs imposed on the firm due to the regulation.[9] Porter and Van der Linde (1995) spawned several papers that studied the effectiveness of environmental regulation on various dimensions of environmental competitiveness (the "strong" version of the PH), which have produced ambiguous findings. The "weak" Porter hypothesis, on the other hand, has also been tested extensively empirically, where the effect of environmental regulation on innovation is mostly found to be positive.[10]

Some studies provide weak evidence in favour of Porter's hypothesis. Popp (2006), for instance, argues that while it is anticipated that stricter environmental policies domestically will have a positive effect on domestic R&D due to induced innovation, the same argument does not necessarily hold for the effects of regulation on innovation across

[9] Ambec et al. (2013) provide a thorough summary of the literature studying the validity of Porter's hypothesis empirically.

[10] Lanjouw and Mody (1996), Brunnermeier and Cohen (2003), Popp (2003), Popp (2006), Vollebergh (2010) all provide empirical studies of the Porter Hypothesis.

countries.[11] Kozluk and Timiliotis (2016) find that there is limited evidence to suggest that domestic environmental regulation has an effect on net exports, overall trade flows or plant location decisions across different industries in the OECD countries.

However, some studies also find weak evidence to support Porter's hypothesis. Aghion et al. (2016) find that firms are more likely to undertake clean innovation in the automotive industry if they are subject to higher fuel prices, and vice-versa for dirty innovation. Lanjouw and Mody (1996) find that the majority of vehicle air emission patents granted in the US were from innovators in other countries, even though the US was the first country to adopt strict emission standards, suggesting that environmental regulations in one country can spur innovation by firms in other countries. An interesting example on the effectiveness of international regulations in stimulating innovation is that of solar photovoltaic (PV) technology, in which China is the industry leader (Dechezleprêtre et al., 2011). The demand for these cells is met almost entirely by industrialised countries such as Germany, Japan, and Spain, where various policies (such as feed-in tariffs, tax rebates, or investment subsidies) have boosted demand for solar energy technologies.

Evidence has also presented the possibility of heterogeneous effects, depending on the type of policy instruments that are used to induce innovation. Hascic et al. (2009) find that regulatory standards have been more important for the development of post-combustion technologies, whereas fuel prices have played a larger role in the development of abatement technologies in the automotive industry. Howell (2016) finds that in response to fuel economy standards in China, domestic firms reduced the quality (and the price) of vehicles compared to foreign firms.

[11] Indeed, Popp (2006) finds that stricter air pollution standards for sulphur dioxide and nitrogen dioxide in the US power sector did not lead to technology transfer from Germany and Japan. Instead, only domestic firms responded positively.

2.2.2 Spillovers along the Global Value Chain

The second sub-strand of literature relevant to this study is that of the spillovers in global value chains (GVCs). Primarily, this literature has studied productivity spillovers taking place within (or across) industries, and flowing from multinational customers to their domestic suppliers. Javorcik (2004) uses firm-level data from Lithuania to show that there are positive productivity spillovers from FDI taking place through contact between foreign affiliates of multinationals, and their local suppliers in the upstream sectors. Interestingly, these spillovers are of an inter-industry nature, i.e.they operate across industries, and are not restricted to suppliers in the same industry.[12] There is some evidence to suggest that in the Chinese automotive industry, both multinationals and Chinese downstream firms have spillovers to local suppliers in terms of the innovative capabilities of these firms (Motohashi and Yuan, 2010).[13]

This paper is also relevant to the stream of literature that has looked at the role of standards in acting as a barrier to trade. Baldwin et al. (2000) categorise standards such as emission limits for vehicles, or fuel economy standards, as "vertical-norm" technical barriers to trade, which may seek to support domestic producers at the expense of foreign producers, for whom the cost of production increases. Maskus et al. (2005) find that compliance with standards imposed by major importing countries raises the short-run production costs (in a sample of developing countries), and that these costs increase as the stringency of the standards increase. An and Maskus (2009) find that mutual recognition agreements (MRAs) where participatory countries recognise each other's testing and certi-

[12] In this paper, we test the "backward linkages" theory put forth in Javorcik (2004). Forward linkages, by converse, would be where environmental performance of downstream firms will depend on innovations undertaken by upstream firms. Costantini et al. (2016), for instance, provide evidence using European data that green innovations that are undertaken by suppliers are capable of enhancing the environmental performance of firms downstream both in the same industry, and across industries.

[13] Javorcik (2004) raises the point that instead of relying on input-output tables to analyse the strength of linkages at the industry level, it will be useful to know the suppliers of each individual firm. Our paper benefits from the use of such data. We are able to identify individual suppliers to a sample of automaker groups, and additionally, we are also able to glean the level at which they supply, which makes it possible for us to be able to understand whether the effects of environmental regulation on the OEMs are able to permeate up the automotive global value chain.

fication procedures plays a positive and significant role in encouraging exports of firms in developing countries, whereas merely imposing similar standards as in developed countries does not play a significant role in inducing higher exports. While we do not study the effect of standards on trade by firms, we find that standards have a positive impact on innovation by suppliers.

Our paper is pertinent to a relatively thin stream of literature in economics on the effects of downstream regulations on upstream innovation outcomes. Greaker (2006) provides a framework against which to study the reverse: he models the channel of influence of upstream innovation on downstream competitiveness through the entry of upstream firms that increase the supply of pollution abatement equipment (after the onset of more stringent environmental policy). Sanyal and Ghosh (2013) finds in an empirical setting that the effects of downstream deregulation in the US electricity sector led to a decline in patenting activity of the upstream firms. Chakraborty and Chatterjee (2017) are closest in spirit to what we do in this paper: they measure the response of upstream firms to an exogenous imposition of German regulation in 1994 on downstream firms in the Indian leather and textile industry (that exported to the German market). They find that the regulation led to an increase in both innovation expenditure, as well as increased technology transfer amongst the upstream firms.

In the next section, we build on these findings from the literature, and derive hypotheses that we then test in the empirical section.

3 Conceptual Framework and Hypotheses

3.1 Innovation by Suppliers in Response to Environmental Regulation Imposed on OEMs

Our first hypothesis concerns the effect of environmental regulation imposed on OEMs on the innovation outcomes of their suppliers. Given the importance of global value chains in the automobile industry, automakers can be expected to demand their suppliers to produce, and thereby innovate in clean technologies in order to meet standards imposed on them. We expect that the OEMs will use their experience on production networks spanning multiple countries, and their bargaining power, to punish suppliers (by switching suppliers, or reducing the price paid on the inputs), if they fail to comply with the standards. Our paper is an addition to the literature on the "forced-linkage" effect, whereby suppliers are forced to improve upon their productivity (or in this case, innovation) due to pressure from multinationals that are their customers (Godart and Görg (2013), Blomström and Kokko (1998), Javorcik and Spatareanu (2009), Gorodnichenko et al. (2010)).

Hypothesis 1: Suppliers are expected to respond positively to environmental regulations that are imposed on the OEMs; as these regulations become more stringent, suppliers will innovate more.

3.2 Regulatory Gap Between Domestic Country and the OEM Countries

Dechezleprêtre et al. (2015) found that the smaller the gap in regulation between the application country where the firm files the patent, and that in the country where the firm is located, the larger will be the transfer of technologies between them, i.e. firms will find it easier to transfer technologies across countries where the regulatory stringency is similar. Technologies generated in developed countries with more stringent environmental regulations are more likely to be transferred to similar countries, due to similar regulatory environment, preferences, and purchasing power, and vice-versa for the technologies invented in the emerging economies.

Extending the argument to suppliers, we hypothesise that firms may innovate more in clean technologies, if the gap between the average OEM regulation that they face (across all countries where they supply components), and the domestic country regulation, is less. The literature provides evidence to suggest that similarity between local market conditions and foreign market conditions will determine the likelihood of firms innovating, and transferring these technologies (Vernon (1979), Dekimpe et al. (2000), Beise and Rennings (2005)). Xie and Li (2015) find, using data from the Chinese automotive industry, that serving customers in disparate geographic locations may hamper innovation and transfer of knowledge between firms. Additionally, they find that firms competing in less separated domestic and overseas markets demonstrate the best innovation performance.

Hypothesis 2: The smaller the "regulatory gap", the higher will be the innovative activity of firms, i.e. more the patents the firm will file in clean technologies.

3.3 Percolation of the Effects of Regulation Down the Automotive Value Chain

Our third hypothesis concerns the percolation of the effects of regulations imposed on downstream firms to innovation by suppliers at various stages of upstream activity.

Javorcik (2004) highlighted that there are three channels through which "backward" spillovers on upstream firms operate: (i) that of direct transfer of knowledge from foreign customers to local suppliers; (ii) emphasis on product quality, which implies that there will be product and process upgrading among suppliers; and (iii) an increased demand for intermediate products from the entry of multinationals, which allows local suppliers to reap the benefits of economies of scale. Hypothesis 3 extends the mechanism of channel ii) up the global value chain. Just as we expect OEMs to demand greater innovation from their immediate suppliers, we can also expect that these suppliers will demand it from their own suppliers, and thus the effects of the regulation will percolate up the value chain.

Hypothesis 3: The effects of more stringent environmental regulation imposed on the OEM are expected to percolate up the global value chain, i.e. the automakers will ensure that tier 1 suppliers increase their efforts towards innovation, the tier 1 suppliers in turn will demand the same from the tier 2 suppliers, and so on.

In the next section, we describe the nature of data that we use for the analysis, along with a description of the empirical approach adopted for the analysis.

4 Data and Methodology

4.1 Data

We use patents as a measure of the innovative activity by firms. The use of patents as a measure of both innovation has both drawbacks and its strengths. Patents may vary in quality and importance (Griliches, 1990); moreover, not all inventions are patented. In this paper, we use granted patents as a measure of innovation, and not just patents that have been applied for, as they are considered high-value patents. There are also several arguments in favour of using patents as an indicator of innovation. Dechezleprêtre et al. (2015) suggest that patent data are highly disaggregated, and thus enable us to identify innovations with specificity. This is particularly true of the automotive industry, where it is possible to obtain information on specific types of technologies (such as auto emissions reduction technologies). In addition, it is possible to get this information for a broad spectrum of firms (unlike data on R&D expenditure, for instance, which is only available for the larger firms). Lastly, the automotive industry is an example of an industry where patents are used frequently as a means of protecting innovations, justifying their use (Aghion et al. (2016), Cohen et al. (2000)).

To extract information on the supplier-OEM links, our source is the ELM Analytics Automotive database (ELM, 2015). The ELM database provides information on the largest OEMs, and their suppliers, along with their respective locations and the level at which they supply the OEMs (tiers 1,2 or 3). This is a survey-based database, with both OEMs and suppliers self-reporting the information. This database does not provide us information on the duration of the relationship between suppliers and OEMs, but we know that at the time of download (June, 2015), that these relationships were still active.[14]

Our source for patent data is the ORBIS Bureau van Dyke (BvD) database, which provides firm-level information on a plethora of indicators, and a means of attributing patents to firms (ORBIS, 2017). Patent information is available on ORBIS since it merged with PATSTAT (the EPO Worldwide Patent Statistical Database). We use ORBIS to extract all patents belonging to different categories of automotive abatement technologies, since our focus is on innovation in clean technologies relevant to the automobile industry in this paper. These patents were identified on the basis of the International Patent Classification (IPC) codes for these technologies (these IPC codes are included in Table B2 in the appendix). These codes have been drawn from Dechezleprêtre et al. (2015), Hascic et al. (2009) and Vollebergh (2010).

ELM is a plant-level database. In order to reconcile the the firms listed in ELM with those in ORBIS, we have matched them manually based on their addresses. Since patent filing is typically carried out at the level of the headquarters, or R&D centre of the firm (and not at the plant level), we have aggregated the information from the ELM dataset to the level of the R&D centre (or headquarters) of the firm in a given country, which we identify from ORBIS based on the address of the firm (in each country) which has the maximum patents. This obviates the need for attributing patents to specific plants of the company, which may or may not be involved in R&D activities. We are able to match most of the firms in the ELM database with the ORBIS database. We then extract patents for these matched firms from ORBIS, and restrict the time dimension of our sample to 2000-2013, due to availability of data on regulation for this time period.

Our final measure of firm-level innovation is the total number of patents granted to

[14] We assume that these relationships were valid for the entire duration of our study, i.e. from 2000-2013. Several references suggest that this may be actually be understating the average duration of the supplier-OEM relationships in the automotive industry, which are not only of long duration, but also relatively similar across automaker groups (Dyer and Chu (2000), Dyer (1996), Kotabe et al. (2003)). We also use varying lengths of the durations in Table B4 in order to check the robustness of our results.

each firm in a given year, summed over all application countries.[15]Given that there are often many firms that may file a patent together, we split each patent across all firms in our sample that have filed it equally, i.e. the patent count variable may take fractional values.

The data sample comprises patent data for 2961 firms (both suppliers, and affiliates of the OEMs) that have been granted a total of 60101 "clean" patents from 2000-2013.[16]. On average, each firm is granted a total of about 7.76 clean patents per year across all countries, and about 109 patents during the entire period and across all application destinations. This boils down to about 4293 patents granted in a year, on average, for all firms.

The coverage of the ELM database is relatively more comprehensive for the North America region, which implies that we have more information on patent filings by firms belonging to the region compared to other regions. We denote the country where the suppliers are based as the "domestic" country, henceforth. The main domestic countries in our sample include the US, Mexico, Brazil, Canada and China, whereas the main application countries in our sample are China, the EPO, the US, Germany, and Japan (firms interested in filing patents in Europe may file patents at the individual patent offices, or at the European Patent Office (EPO) which gives them patent protection across the EU).

In the appendix, we include some graphs that illustrate descriptives that are relevant to our analysis. Figure A1 includes a plot of the total number of clean patents granted to all firms across all application countries by year. We see that the total clean patents granted across all firms in our sample marginally increased up till 2008, and thereafter started declining. This is in line with the start of the financial crisis, and the expected decline in innovative activity thereafter (WIPO, 2010).[17]

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[15] As a robustness check in Table B5, we also include the results of using total clean patents granted to a firm by each application country, as an alternative dependent variable. The main results still hold.

[16] we only use the sample of of suppliers for the models that we estimate below

[17] This may also be driven by the delay in registration of patents; it can take up to 18 months to grant a patent.

In Figure A2, we plot total patents granted to firms across different application countries. The countries/regions included here are the US, China, Japan, and the EU (for which we mention patent filings in the EPO). We can infer from this figure that for the largest automobile manufacturing markets such as the US, Japan and Europe, the number of patent filings have declined over time. On the other hand, we see a steep rise in patent filings in the Chinese market (the large share of which is driven by patent filings by Chinese firms, but also by firms located in other countries). In Figure A3, we plot the total patent filings by domestic country for the countries having the most firms based there: the US, Japan, China and Mexico. These graphs suggest that patent filings have increased over time for Chinese and Japanese firms, while they have declined for firms based in the US and Mexico.

The database that we use to draw data on environmental regulation is the International Council on Clean Transportation (ICCT) data table on global passenger vehicle standards (ICCT, 2015). This has compiled data on environmental regulations imposed on passenger vehicles across a sample of countries and regions, namely Japan, the European Union, United States, Canada, China, South Korea, Mexico, Brazil, and India.[18] The benefit of using this dataset is that it enables comparisons of regulations across countries, taking into account differences in test driving cycles, and the physical units of measurement of the standards. As a measure of environmental regulation in different countries, we use the New European Driving Cycle (NEDC) measure of grams of carbon dioxide (CO_2) emissions permitted per kilometre. We use the measure applicable for LDVs (light duty vehicles), which includes both cars and light commercial vehicles.

In this paper, we use emission standards for CO_2 (which are equivalent to fuel efficiency standards for CO_2). This is because of the difference in methods of testing and calculation for emission standards for pollutants such as NO_X, HC and CO differ across

[18] These markets constitute almost 80% of the total passenger vehicle sales in 2013, which renders the environmental regulations implemented in these markets as an important determinant of not just manufacturing decisions of automaker groups, but certainly also innovation.

countries, primarily due to differences in test cycles. Test cycles differ across countries in factors such as test length, duration, the maximum speed and acceleration, and the percentage of time idling (TransportPolicy.net, 2017). We thus use data on emission standards for CO_2 provided by the ICCT, which have been converted to a common denomination (both in terms of physical units, and in the parity of testing cycles), enabling easy benchmarking across jurisdictions.

Figure A4 below plots the evolution of the emission standard for LDVs across all countries in our sample, by time. It is clear that the standard has become more stringent over the years, as maximum permissible CO_2 emissions have become capped at lower levels. Figure A5 plots the evolution of these standards in different countries in the sample. Standards have become stricter over time for all countries. Moreover, we see that all countries seem to have converged to similar regulations towards the end of the period (Perkins and Neumayer, 2012).

Table 1 below presents the summary statistics. The units of the emission standard variables are grams of carbon dioxide (CO_2) emissions permitted per kilometre, and they are lagged by one year. Firms file approximately 8 patents in a given year in clean technologies (across all destinations or application countries). We find that on average, the emission standard in the domestic countries of the suppliers (211.70 gms of CO_2 per kilometre) is weaker than that in the application countries (176.97 gms of CO_2 per kilometre).[19] This may be because suppliers are more likely located in developing countries, which have weaker standards on average than the developed countries. Moreover, it is also clear from this table that the emission standard is more stringent for firms that are suppliers at the tier 3 level, which in turn is stronger than for firms supplying at tier 2, and it is weakest for firms supplying at tier 1.

[19] Since the regulation is measured in terms of grams of the pollutant permitted per kilometre, a lower value of the standard represents a more stringent regulation.

Table 1: Summary Statistics

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
Number of clean patents granted to firm i in year t	89180	7.76	37.22	0	572.2
Number of clean patents granted to all firms based in a given country	82810	2233.23	1752.46	0	4277.3
Number of clean patents granted to firms filing in a given application country	76440	4173.26	2305.31	0	7248.6
Average emission standard in OEM countries (entire sample of suppliers)	76193	84.84	88.60	0	240
Average emission standard in OEM countries (tier 1 suppliers)	72176	183.40	27.77	0	240
Average emission standard in OEM countries (tier 2 suppliers)	14378	175.69	20.54	42.34	240
Average emission standard in OEM countries (tier 3 suppliers)	5902	164.29	18.50	127	240
Emission standard in domestic country (where firm is based)	70162	211.70	25.50	127	252
Emission standard in application country (where firm files patents)	66238	176.97	30.47	127	252

4.2 Methodology

Our approach in this paper is to estimate the patenting activity of suppliers in response to regulations that they face from the OEMs. In terms of the empirical methodology, we adopt a Poisson estimation methodology, given that our dependent variable is a count variable.[20] In order to study the role of OEM regulation on patenting activity, the basic model that we estimate is as follows:

$$P_{ijt} = exp(\beta_0 R_{i,t-1} + \beta_1 R_{j,t-1} + \beta_2 RG_{j,i,t-1} + \beta_3 S_{j,t-1} + \beta_4 KPAT_{i,t-1} + \mu_i + u_t) + \epsilon_{i,j,t} \quad (1)$$

where P_{ijt} measures the clean patents granted to supplier i located in domestic country j in year t (summed over all application countries). The main explanatory variable in the above specification is the OEM regulation facing firm i in period t-1 (denoted by $R_{i,t-1}$). The OEM regulation is created as a weighted average of the emission standards in the countries where the OEMs are located to which firm is supplying. The weights are

[20] One common argument against using the Poisson estimation is that often, count models may suffer from over-dispersion of data. Cameron and Trivedi (2009) suggest that there are two ways of getting around this: one is to estimate a negative binomial model, and the other is to simply use robust clustered standard errors in the Poisson model. We adopt the latter methodology in this paper.

dummies for whether the firm supplies that OEM or not (at any tier, 1, 2 or 3).[21] Model 1 is useful in testing Hypotheses 1 and 2 of the previous section.

We also introduce the domestic regulation in the country j where firm i is based, in period t-1 (denoted by $R_{j,t-1}$) as an independent variable. In order to test Hypothesis 2, we include a variable measuring the regulatory gap $RG_{j,i,t-1}$, where the gap is defined as the absolute difference between the average OEM regulation faced by the supplier i and the domestic regulation in period t-1 (namely $|R_{i,t-1}$- $R_{j,t-1}|$).

In this basic model, we use the same controls as were used in Dechezleprêtre et al. (2015). The first control is the stock of clean patents in automotive technologies granted to all the firms based in country j in period t-1 (denoted by $S_{j,t-1}$), except . This variable accounts for the technological capabilities of firms in domestic country j in innovating new technologies. The second control is the stock of all patents (across all categories of technologies, not just abatement technologies) previously filed by firms in the application countries where firm i is filing patents. We sum this variable over all application countries where firm i is filing patents, to maintain conformity with our dependent variable.[22] This variable is useful in capturing the absorptive capacity for new technologies in the countries where firm i is filing patents.

The expected sign of the coefficient for the first control is thus positive, while the second control may have either a positive or negative effect on innovation by firm i, depending on whether the technologies which firm i is filing patents for, and those already included in the stock are complements or substitutes. We use the lagged version of this

[21] The OEM regulation variable takes the form $R_{i,t-1} = \sum_n D_{i,n} R_n / \sum_n D_{i,n}$, where $D_{i,n}$ denotes a dummy for whether firm i supplies OEM n, and R_n denotes the emission standard in the country where OEM n is based.

[22] We calculate this variable following the perpetual inventory methodology of Peri (2005):

$$KPAT_{i,t} = \sum_k [(1-\delta)PAT_{i,k,t-1} + PAT_{i,k,t}] \quad (2)$$

where $PAT_{i,k,t}$ refers to the total number of patents granted in the application countries (k) of firm i in period t; following Dechezleprêtre et al. (2015), we set the depreciation rate of R&D, δ, to be equal to 15%.

variable (in period t-1) as a control to correct for possible endogeneity.

One concern with this estimation may be endogeneity, given that environmental regulations in the automobile industry are often decided after consistent lobbying efforts by firms (Wagner, 2012). We use lags to address potential endogeneity concerns, and to acknowledge that suppliers' responses to changes in regulations need not be instantaneous.[23]

In the baseline estimation, we include firm fixed effects (denoted by μ_i), along with application country and year (u_t) fixed effects. Firm fixed effects are useful in controlling for uncontrollable factors that are time-invariant at the level of the firm (such as their general technological capability, and specifics of their relationship-specific investments with the OEMs). Time fixed effects may be effective in controlling for unobservable factors that influence all firms in a given year, such as the reduction in demand for automobiles during periods of economic downturn, and variations in fuel prices over time that are common to all firms. The results of estimating Hypothesis 1 and Hypothesis 2 are provided in Table 2 below.

In order to test Hypothesis 3 regarding the spread of the effects of downstream regulation up the supply chain, we replace $R_{i,t-1}$ in model 1 above by the OEM regulations for suppliers at tier 1, tier 2 and tier 3 respectively (i.e. three separate regulation variables are created for each tier of supplier firms, thus three separate estimations are carried out). These variables are also defined as a weighted average of the emission standards in the countries of location of the OEMs, but the weights are now dummies for whether the firm specifically supplies the given OEM at tier 1, 2 or 3 or not.[24][25] These results are provided in Table 3.

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[23] Table B7 in the appendix includes the results of using the second lag of the emission standard instead of the first, as a robustness check.

[24] The OEM regulation variables now take the form $R_{i,t-1} = \sum_n D_{i,n} R_n / \sum_n D_{i,n}$, where $D_{i,n}$ denotes a dummy for whether firm i supplies OEM n at tier 1, 2 or 3, and R_n denotes the emission standard in the country where OEM n is based.

[25] We also estimate model 1 above using all three regulation variable simultaneously, but this is not our baseline estimation, because few firms supply at all three tiers, considerably shrinking our sample.

5 Results

5.1 Empirical Results

Table 2 below presents the results of the main estimation results for the entire sample of suppliers, while Table 3 provides the results disaggregated by the tier. In column (1) of Table 2, we present the results of estimating Model 1, first without introducing the OEM regulation. While we find that stronger domestic regulation is associated with the granting of more patents, we do not find a similar effect either for the application country regulation (which is averaged across all application country where firm i patents). We find that the lagged domestic patent stock in environmentally-friendly automotive technologies is another factor that plays a positive and significant role in the total innovation by the firm, whereas the higher the sum of patents filed across the application countries of firm i, the lesser are its own patent filings.

Column (2) of Table 2 presents the main results of the estimation, eschewing from the application country dimension, and instead testing whether the OEM regulation plays a role in determining innovation in clean technologies. This is our baseline specification. We find that stricter regulations faced by the suppliers from their customers (i.e., a lower value of the OEM regulation variable) are more likely to lead to a higher number of patents filed, while controlling for domestic regulation, providing evidence in support of Hypothesis 1. Additionally, we find that the regulatory gap variable is also significant at the 1% level, and that the smaller the gap, the more likely are suppliers to innovate (in support of Hypothesis 2). These results are robust when we introduce the average regulation across the application countries where firm i files for patents in column (3). The interpretation of the coefficient of the OEM regulation variable is as follows: as the average emission standard decreases by 1 gram of CO_2 per kilometre, firm i likely to file 6.2% more patents.

Dechezleprêtre et al. (2015) suggest that the coefficient on the domestic country regulation may also have a negative sign, as our results in columns (2) and (3) suggest. They suggest two possible reasons for this. One is the costliness of clean innovations, which implies that firms may patent less domestically as the stringency of regulation increases. Secondly, they may then also spend less resources patenting in other countries, to divert these resources towards domestic innovation.

Table 2: Regression Results for the Suppliers: Poisson Estimation

Dep. Var.: Number of clean patents granted to firm i in year t	(1)	(2)	(3)
OEM Regulation		-0.062***	-0.071***
		(0.007)	(0.010)
Regulatory Gap (Customer- Domestic)		-0.062***	-0.071***
		(0.007)	(0.010)
Domestic Regulation	-0.014***	0.051***	0.059***
	(0.002)	(0.007)	(0.009)
Average Regulation Across Countries of Patent Filings	0.036***		0.039***
	(0.003)		(0.003)
Domestic Country Patent Stock	0.484***	0.415***	0.376
	(0.054)	(0.058)	(0.061)
Patent Stock Summed Over Recipient Countries	-0.520***	-0.480***	-0.526***
	(0.046)	(0.047)	(0.047)
Observations	59448	63312	56065

Notes: All specifications include firm fixed effects, year fixed effects, and application country fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported.

In Table 3, we attempt to provide some evidence of the percolation of the effects of these regulations up the global automotive value chain. In columns (1) and (2), we include the results relevant for the tier 1 suppliers, columns (3) and (4) present the results for the tier 2 suppliers, whereas the results of columns (5) and (6) are valid for suppliers at tier 3. The results of columns (1), (3) and (5) (our baseline specification) highlight that the positive (and significant at the 1%) effect of stronger OEM regulation on innovative activity of suppliers persists across tiers; moreover, the smaller the regulatory gap, the greater the patenting activity. While we cannot compare the magnitudes of the coefficients directly across columns, the magnitude of the marginal effect is increasing for more upstream suppliers: as the emission standard decreases by 1 gram of CO_2 per kilometre, a tier 1 supplier is more likely to file 1.5% more patents, a tier 2 supplier is more likely to file 2.5% more patents, while a tier 3 supplier is more likely to file 16% more patents.

In column (7), we present the results of the estimation introducing the regulation variables at each of the three tiers simultaneously in the same specification. This estimation, thus, only includes firms that are supplying at all three tiers (1, 2 and 3), given the fixed effects estimation methodology. We find that stricter regulation on the OEMs for tier 3 suppliers has a positive effect on innovation. We find the converse for firms supplying at tier 2, while the effect of OEM regulation on innovation by tier 1 suppliers is insignificant. Firms that supply at all three levels are typically large multinational corporations themselves; we suspect this result may be driven by a substitution within these firms from innovation by more downstream suppliers to more upstream suppliers (Chakraborty and Chatterjee, 2017).

In Table 4, we provide some additional results to test if there is a difference in innovation outcomes of suppliers belonging to developed countries, and those belonging to developing countries. We interact the variables for the regulation at different levels with an indicator for whether the supplier is based in a developing country. The results of column (1) includes the estimation for the entire sample of suppliers, and suggests that as before, stricter regulations are more likely to lead to higher levels of innovation; there is no difference in the strength of this effect between developed and developing countries (the interaction term between the OEM regulation and the indicator for being located in a developing country is insignificant). Columns (2) to (4) present the results separately for the three tiers, and we find this effect persists for the tier 2 and 3 firms (for whom the interaction effect is insignificant, suggesting identical effects for firms in both developed and developing countries). However, the results of column (2) suggest that tier 1 suppliers in developing countries are less likely to file patents in response to stricter regulations, contrary to tier 1 suppliers in developed countries.

As regards the regulatory gap, the results of column (1) suggest that the smaller this

Table 3: Regression Results for the Suppliers by Tier: Poisson Estimation

Dep. Var.: Number of clean patents granted to firm i in year t	(1)	(2)	(3)	(4)	(5)	(6)	(7)
OEM Regulation- Tier 1	-0.015***	-0.015***					0.589
	(0.002)	(0.002)					(0.486)
Regulatory Gap (OEM- Domestic) Tier 1	-0.013***	-0.013***					
	(0.002)	(0.002)					
OEM Regulation- Tier 2			-0.025***	-0.020**			0.082***
			(0.009)	(0.009)			(0.010)
Regulatory Gap (OEM- Domestic) Tier 2			-0.023***	-0.018**			
			(0.009)	(0.009)			
OEM Regulation- Tier 3					-0.096***	-0.160***	-0.110***
					(0.026)	(0.030)	(0.024)
Regulatory Gap (OEM- Domestic) Tier 3					-0.048**	-0.112***	
					(0.026)	(0.029)	
Domestic Country Regulation	0.002	0.001	0.398	-0.009	0.061**	0.125***	0.118***
	(0.003)	(0.003)	(8.601)	(0.009)	(0.028)	(0.031)	(0.041)
Average Regulation Across Countries of Patent Filings		0.037***		0.006		0.242	0.383
		(0.003)		(0.005)		(6.599)	(7.090)
Domestic Country Patent Stock	0.420***	0.390***	0.802***	0.713	0.399***	0.138	0.786
	(0.060)	(0.063)	(0.088)	(0.094)	(0.195)	(0.234)	(25.530)
Patent Stock Summed Over Recipient Countries	-0.494***	-0.539***	0.151	0.389	-0.491	-0.484	-0.458***
	(0.048)	(0.048)	(0.512)	(0.544)	(0.172)	(0.178)	(0.020)
Observations	60263	53365	12015	10943	5193	4915	3925

Notes: All specifications include firm fixed effects, year fixed effects, and application country fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported.

gap, the greater the number of patents granted; however, this effect is absent for the firms in developing countries (the interaction term has a positive coefficient). We observe this for tier 1 suppliers, while for tier 2 suppliers, there is no difference between suppliers in developed and in developing countries (as is suggested by the results of columns (2) and (3), respectively).

Thus, we find that at the downstream levels of the value chain, there is a significant difference between suppliers in developed and developing countries. Tier 1 suppliers in developed countries respond positively to stricter regulations on the OEMs, whereas the effect is reversed for tier 1 suppliers based in developing countries. This difference in outcomes is not observed either for the firms at the upstream levels of the chain.

Table 4: Regression Results for the Suppliers (Developed vs. Developing Countries): Poisson Estimation

Dep. Var.: Number of clean patents granted to firm i in year t	(1) All	(2) Tier 1	(3) Tier 2	(4) Tier 3
OEM Regulation	-0.081***	-0.067***	-0.033***	-0.070***
	(0.007)	(0.009)	(0.012)	(0.029)
OEM Regulation* Indicator for Firm Based in Developing Country	0.011	0.047***	-0.005	-0.086
	(0.007)	(0.007)	(0.012)	(3.124)
Regulatory Gap (OEM-Domestic)	-0.081***	-0.065***	-0.031***	-0.022
	(0.007)	(0.009)	(0.012)	(0.029)
Regulatory Gap (OEM-Domestic)* Indicator for Firm Based in Developing Country	0.060***	0.055***	0.011	-0.056
	(0.009)	(0.010)	(0.014)	(0.036)
Domestic Country Regulation	0.040***	0.024***	-0.001	0.079***
	(0.006)	(0.004)	(0.009)	(0.031)
Domestic Country Patent Stock	0.732	0.689***	0.782***	0.004**
	(0.062)	(0.060)	(0.093)	(0.002)
Patent Stock Summed Over Recipient Countries	-0.472	-0.488***	0.145	-0.493***
	(0.048)	(0.048)	(0.514)	(0.171)
Observations	63312	60263	12015	5193

Notes: All specifications include firm fixed effects, year fixed effects, and application country fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported. The developing countries in the sample include Argentina, Bosnia and Herzegovina, Brazil, China, India, Indonesia, Iran, Morocco, Mexico, Malaysia, Philippines, Pakistan, Romania, Russian Federation, Thailand, Turkey and South Africa.

5.2 Additional Tests and Robustness Checks

Tables B4 to B7 in the appendix include the results of the robustness checks. In Table B4, we present the results assuming shorter durations for the length of the relationship between the suppliers and the OEMs. Columns (1) to (4) include the results assuming that the relationship was holding for the last 3 years, columns (5) to (8) include the results assuming 5 years, whereas the estimations in columns (9) to (12) use 10 years of data. The results suggest that our main finding regarding the positive effect of stricter OEM regulation on patenting activity is valid for different durations for the entire sample of suppliers (as the negative coefficient on this variable in columns (1), (5) and (9) suggest). It is also clear from the results of these columns that a smaller regulatory gap has a positive effect on innovation by suppliers. The positive effect of regulation on innovation persists for tier 1 suppliers across durations (columns (2), (6) and (10)) and for tier 3 suppliers (columns (4), (8) and (12)) , whereas OEM regulation is insignificant for the tier 2 firms.

In Table B5, we use a stricter identification strategy, where we use the patents granted in each application country (rather than the sum of patents granted across all application countries) as the dependent variable, and instead of using firm fixed effects, we incorporate a stricter specification with firm-by-application country fixed effects. This is effective in capturing the effects of unobservables at the level of the firm-destination which are not changing over time, such as the particular nature of the relationship between the suppliers and the OEMs, which may not be captured by taking firm-level fixed effects. In these results, we find similar results to those in Tables 2 and 3 in the text: stricter OEM regulation leads to greater transfers of technology, as can be inferred from the results of columns (1) (for the entire sample of suppliers), (2) (tier 1 suppliers), (3) (tier 2 suppliers) and (4) (tier 3 suppliers). Likewise, the coefficient on the regulatory gap has a negative coefficient for the sample of tier 1 firms (it is insignificant for the firms at the 2nd or 3rd tiers). This table shows that the main results of this paper are valid even with a stricter specification, which controls for unobservables at the firm-patent destination level.

In Table B6, we use an alternative definition of the regulation variable. Given the possibility that suppliers may be undertaking innovation in response to the strictest regulation that they face from their OEMs (instead of the average regulation across OEMs), we construct the OEM regulation variable as the strictest (i.e. least non-zero emission standard) facing the suppliers. Column 1 presents the results for the overall sample of suppliers, while columns 2,3 and 4 include the results for tiers 1, 2 and 3 respectively. The results of column 1 suggest that stricter OEM regulation has a negative effect on innovation, when we use the maximum regulation. We find that for tier 1 suppliers, emission standards defined using the strictest standard faced is an insignificant determinant of innovation (column (2)). In columns (3) and (4), we find a positive effect of regulation on innovative activity of the tier 2 and 3 suppliers. On the other hand, we find that the regulatory gap has a consistently negative and significant effect on supplier innovation, i.e. the smaller the gap, the greater will be the innovative activity of the suppliers.

These results are in contrast to those that we found using the average regulation as a determinant of innovative activity. However, they are intuitive; Dechezleprêtre et al. (2015) suggest that OEMs do not export (or produce) the same after-treatment and base-engine technologies in all the markets that they operate in. This is because there are costs to innovating in (and transferring) more sophisticated clean technologies. They highlight that vehicles that are built to meet stricter standards will be more expensive in their respective markets, which means that OEMs may be constrained to meet local regulations in each market, rather than extending the same technology (or production process) across markets. This is also in line with the findings of Bauner (2007) and Gallagher (2006).

6 Conclusion

The results of our paper have interesting policy implications in the context of spurring clean innovation by firms involved in vertical production linkages in a global value chain. The finding in this paper that suppliers respond to stricter environmental regulations by innovating more suggests that there may be positive externalities (or spillovers) of environmental regulation. The evidence that we present on the effectiveness of regulations that are imposed on automakers in inducing innovation by suppliers provides some support in favour of targeting downstream firms with policy instruments, who can then send signals to the upstream firms (rather than targeting firms along the entire value chain

(Calcott and Walls, 2000).

The finding of our paper on smaller regulatory gaps leading to greater innovation by firms also provides some support in favour of homogenisation (or harmonisation) of standards, which has been put forth in the trade literature as a means of reducing the barriers to trade (Portugal-Perez et al., 2010).Lastly, our finding about heterogeneity of effects for firms based in developed countries and in developing countries suggests that policy-makers in developing countries may benefit from providing incentives (such as R&D subsidies, tax breaks, etc.) to suppliers to undertake innovation.

There are some caveats to the results that we provide in our analysis. Firstly, while we have some information on the parts that are produced by the suppliers, we do not have information in our data on the volume of trade between the suppliers and the OEMs, or the total output produced by them. This may be useful for evaluating the importance of these suppliers to the OEM.

Secondly, while we are able to identify the suppliers based on the tier at which they supply the OEM, we do not know the exact chain of production, i.e. we do not know the tier 2 suppliers that are customers of the tier 3 suppliers, the tier 1 suppliers that are customers of the tier 2 suppliers, etc. It would be a useful addition to this paper to use such data for analysis, in order to better understand how the effects are exactly transmitted up the value chain.

It would be fruitful for future research to study the effect of regulation on innovation by affiliates of OEMs, and compare it to innovation responses of suppliers. In the availability of data on private standards, it may also be interesting to understand whether private standards imposed by the OEMs on their suppliers have a positive effect on their innovation outcomes, and whether this effect is stronger than the effect of public environmental regulations.

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Appendix A Figures

Figure A1: Total Clean Patents Filed by all Firms, by Year (Source:ORBIS)

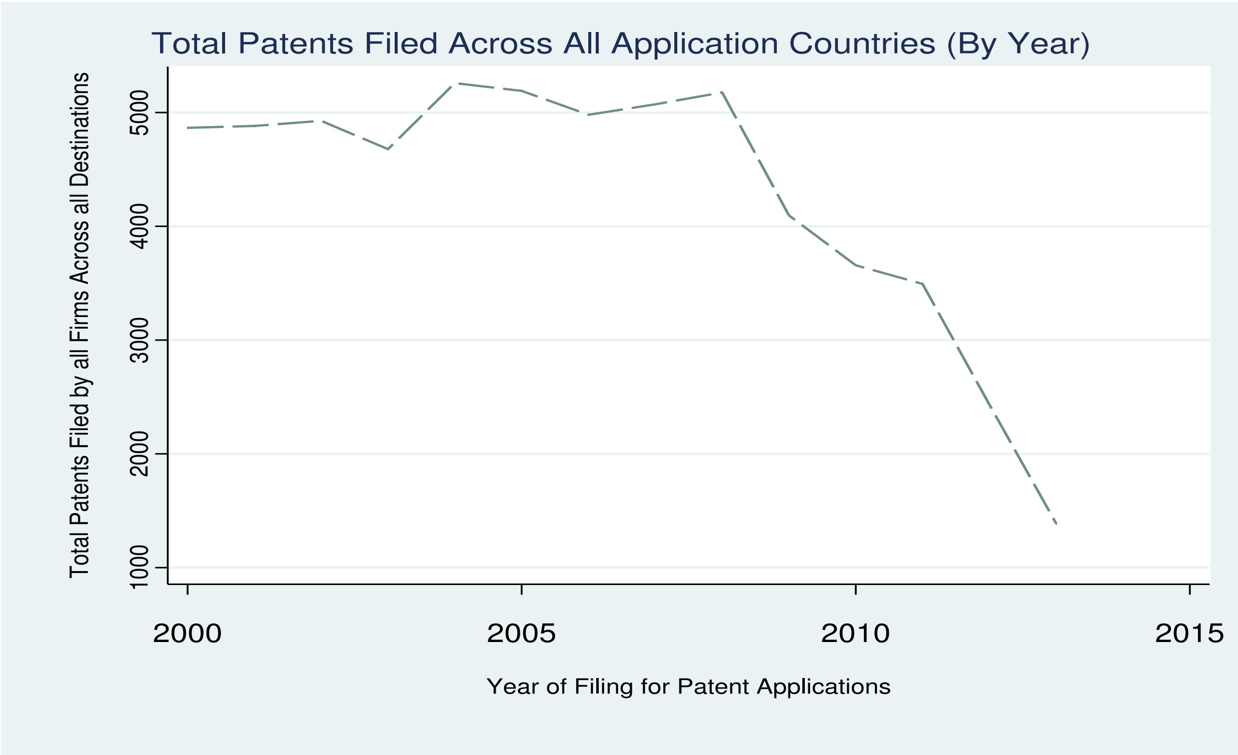


Figure A2: Total Clean Patents Filed by all Firms by Application Country , and by Year (Source: ORBIS)

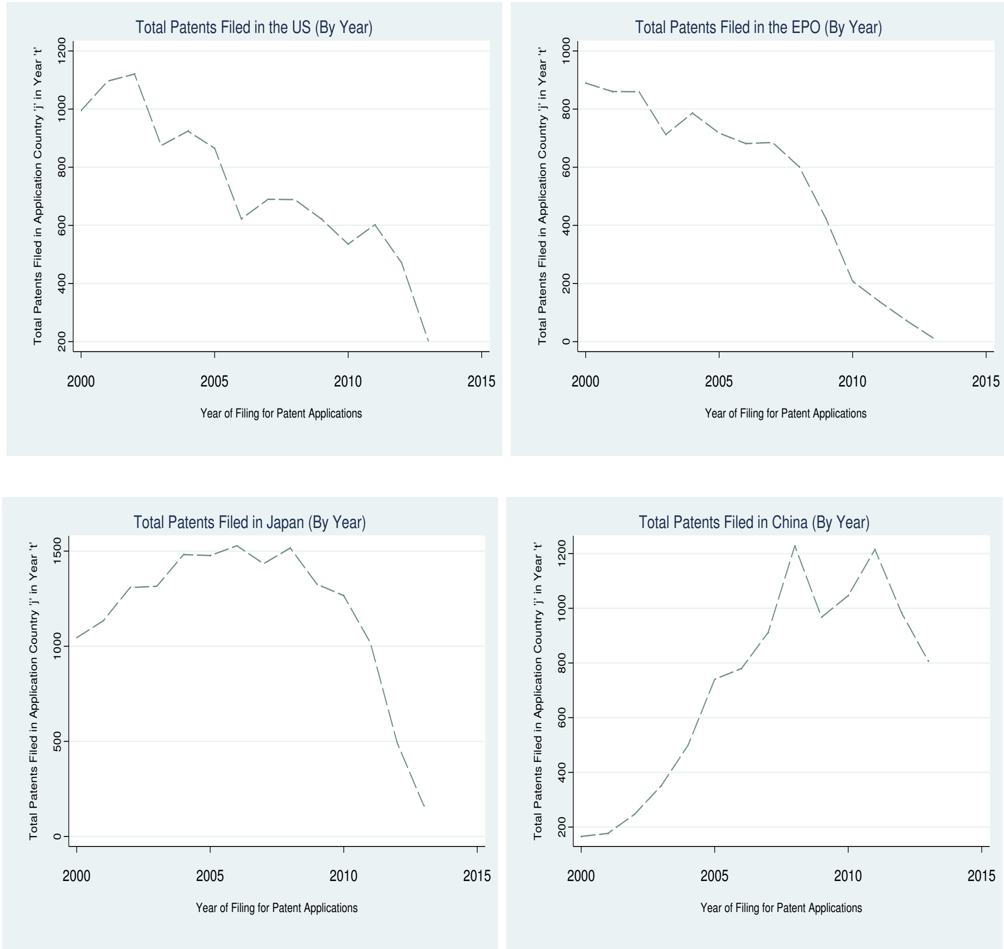


Figure A3: Total Clean Patents Filed by all Firms in Inventor Country and by Year (Source: ORBIS)

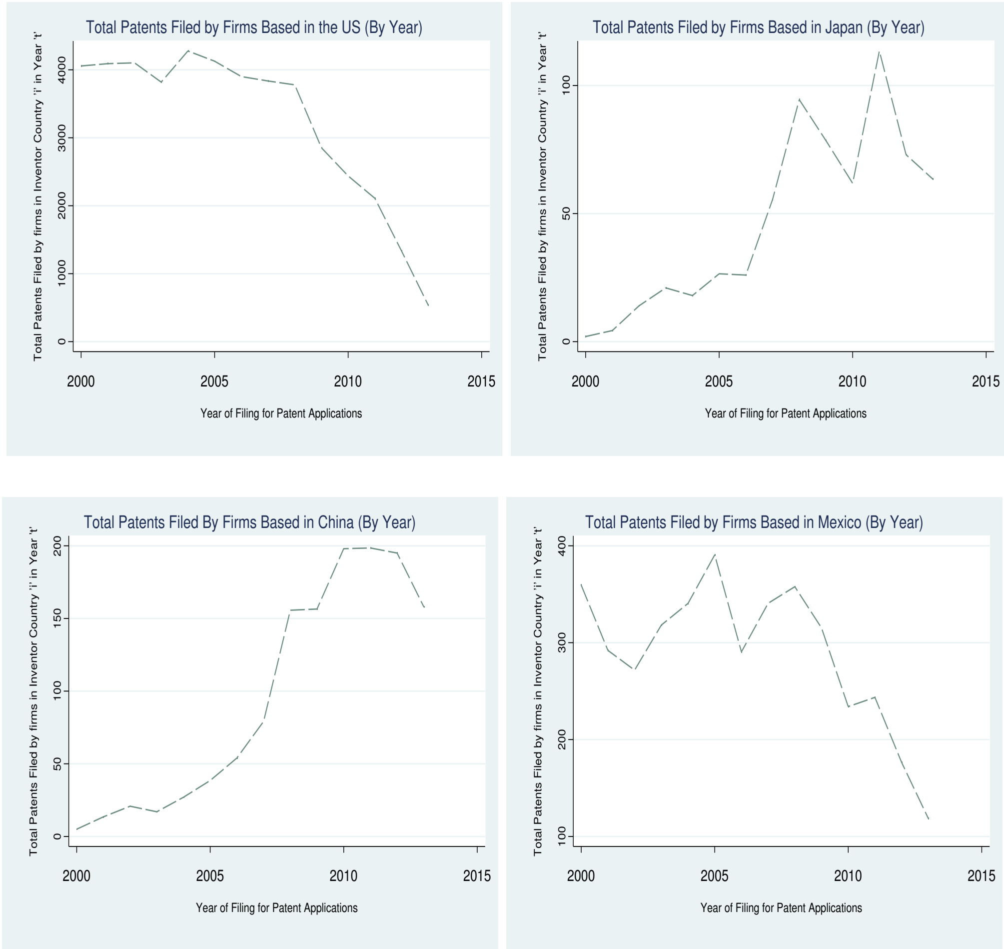


Figure A4: Emission Standard (Grams of CO_2 per Kilometre) Averaged Across Countries by Year (Source:ICCT)

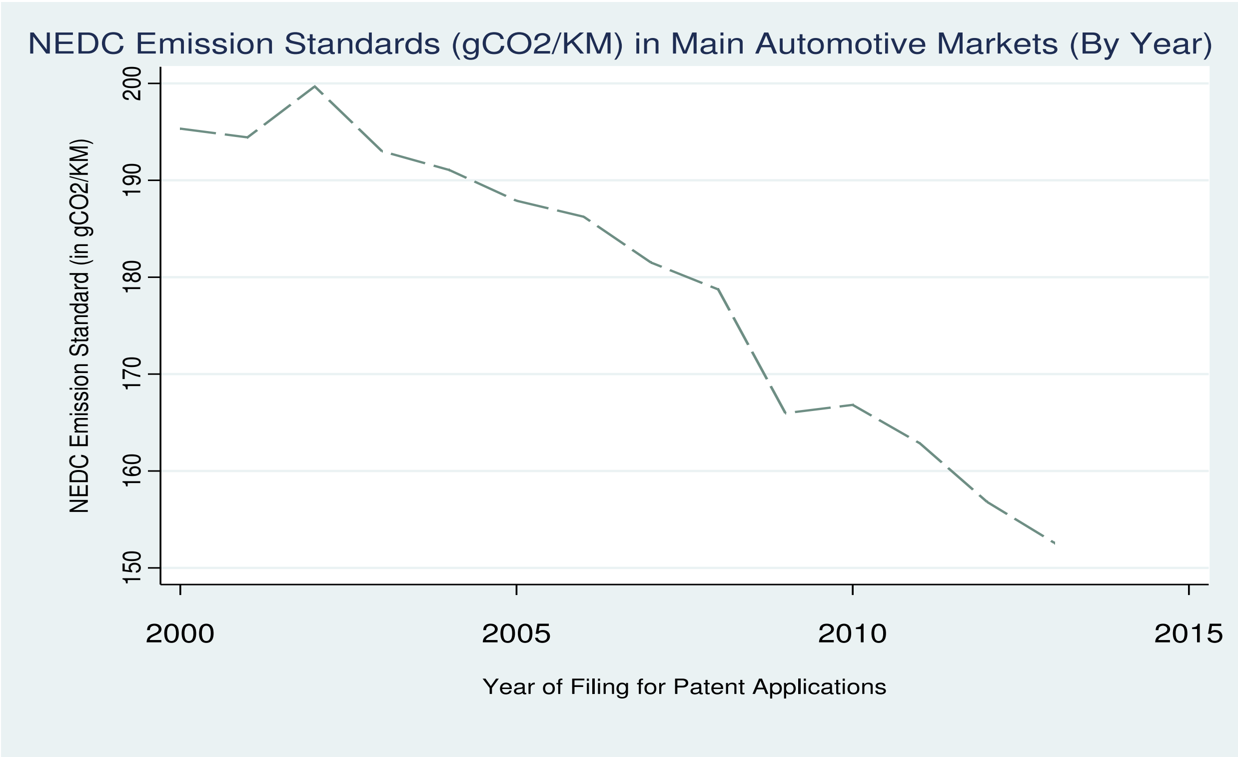
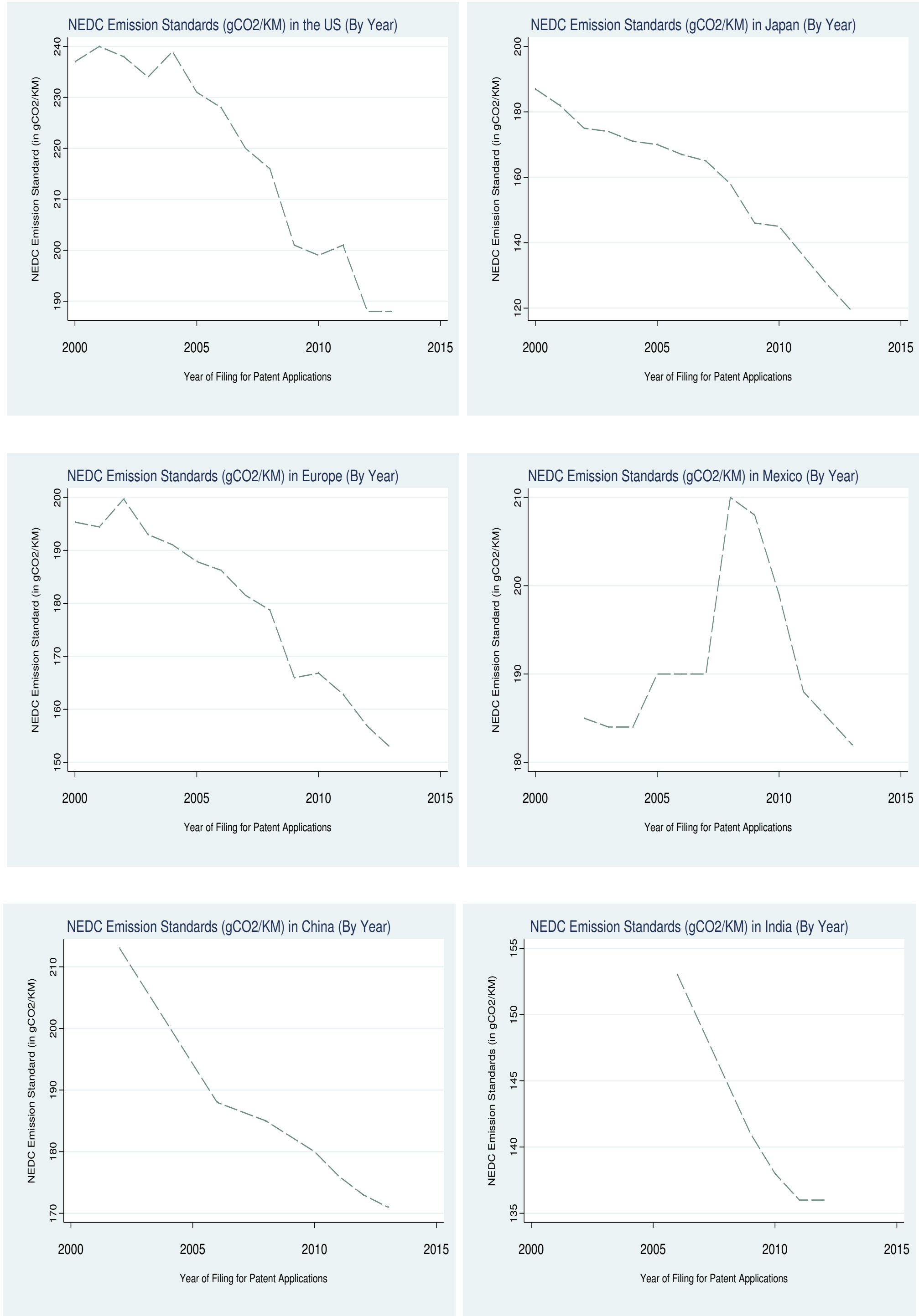


Figure A5: Emission Standard (Grams of CO_2 per Kilometre) By Country and Year (Source: ICCT)



Appendix B Tables

Table B1: Original Equipment Manufacturers (OEMs) and Countries of Origin

Name of OEM	Country of Origin
AM General	United States of America
American Honda	United States of America
Audi	Germany
BMW	Germany
Daimler AG	Germany
Fiat Chrysler Automobiles	Italy
Fiat SpA	Italy
Ford Motor Company	United States of America
Ford Britain	Great Britain
Ford Werke	Germany
General Motor Corporation	United States of America
General Motors Daewoo	South Korea
General Motors Mexico	Mexico
Great Wall Motors	China
Hino Motors	Japan
Honda Mexico	Mexico
Honda Motors	Japan
Hyundai Motors	South Korea
Hyundai North America	United States of America
Isuzu Motors	Japan
Jaguar	Great Britain
Kia Motors	South Korea
Maserati	Italy
Mazda Motor Corporation	Japan
Mercedes Benz US	United States of America
Mitsubishi Motors	Japan
Mitsubishi North America	United States of America
Nissan Motors	Japan
Nissan Mexico	Mexico
Opel	Germany
Peugeot	France
Subaru North America	United States of America
Suzuki Motors	Japan
Tesla Motors	United States of America
Toyota Motor Corporation	Japan
Toyota North America	United States of America
Volkswagen	Germany
Volkswagen Mexico	Mexico

Table B2: IPC Codes Relevant for Automotive Emissions Control

IPC Code	Description
	Air-fuel ratios
F01N 3/05	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust by means of air e.g. by mixing exhaust with air
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
F02M 23	Apparatus for adding secondary air to fuel-air mixture
F02M 25	Engine-pertinent apparatus for adding non-fuel substances or small quantities of secondary fuel to combustion-air, main fuel, or fuel-air mixture
F02M 3	Idling devices
	Oxygen, NO_X and temperature sensors
F01N 11/00+	Monitoring or diagnostic devices for exhaust-gas treatment apparatus
F02D 41/14	Electrical control of supply of combustible mixture or its constituents (introducing closed-loop corrections)
G01M 15/10	Testing of internal-combustion engines by monitoring exhaust gases
	Fuel injection systems
F02M 39/00+	Arrangements of fuel-injection apparatus with respect to engines; Pump drives adapted to such arrangements
F02M 41/00+	Fuel-injection apparatus with two or more injectors fed from a common pressure-source sequentially by means of a distributor
F02M 43/00+	Fuel-injection apparatus operating simultaneously on two or more fuels or on a liquid fuel and another liquid, e.g. the other liquid being an anti-knock additive
F02M 45/00+	Fuel-injection apparatus characterised by having a cyclic delivery of specific time/pressure or time/quantity relationship
F02M 47/00+	Fuel-injection apparatus operated cyclically with fuel-injection valves actuated by fluid pressure
F02M 49/00+	Fuel-injection apparatus in which injection pumps are driven, or injectors are actuated, by the pressure in engine working cylinders, or by impact of engine working piston
F02M 51/00+	Fuel injection apparatus characterised by being operated electrically
F02M 53/00+	Fuel-injection apparatus characterised by having heating, cooling, or thermally-insulating means
F02M 55/00+	Fuel-injection apparatus characterised by their fuel conduits or their venting means
F02M 57/00+	Fuel injectors combined or associated with other devices
F02M 59/00+	Pumps specially adapted for fuel-injection and not provided for in groups F02M 39/00 to F02M 57/77
F02M 61/00+	Fuel injection not provided for in groups F02M 39/00 to F02M 57/00
F02M 63/00+	Other fuel-injection apparatus, parts, or accessories having pertinent characteristics not provided for
F02M 65/00+	Testing fuel-injection apparatus, e.g. testing injection timing
F02M 69/00+	Low-pressure fuel-injection apparatus
F02M 71/00+	Combinations of carburettors and low-pressure fuel-injection apparatus
	Exhaust gas recirculation (EGR) valves
F01N 5/00+	Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy
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
F02D 21/06-10	Controlling engines characterised 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
F02M 25/07	Engine-pertinent apparatus for adding exhaust gases to combustion -air, main fuel, or fuel-air mixture
	On-board diagnostics systems
F02D 41/00+	Electrical control of combustion engines; Electrical control of supply of combustible mixture or its constituents
F02D 43/00+	Conjoint electrical control of two or more functions, e.g. ignition, fuel-air mixture, recirculation, supercharging, exhaust-gas treatment
F02D 45/00+	Electrical control not provided for in groups F02D 41/00 to F02D 43/00
F01N 9/00+	Electrical control of exhaust gas treating apparatus
	Crankcase emissions and control
F01M 13/02- 04	Crankcase ventilating or breathing; having means of purifying air before leaving crankcase, e.g. removing oil
	Catalytic converters, lean NO_X catalysts, NO_X absorbers, catalytic regeneration technology
F01N 3/08-34	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust; for rendering rendering innocuous by thermal or catalytic conversion of noxious components of exhaust
B01D 53/92-96	Separation of gases or vapours; recovering vapours of volatile solvents from gases; chemical or biological purification of engine exhaust gases; regeneration, reactivation, or recycling of reactants
B01J 23/38-46	Catalysts comprising metals or metal oxides or hydroxides; of the platinum group metals
	Thermal reactor
F01N 3/26	Exhaust apparatus having means for rendering innocuous, by thermal conversion of noxious components of exhaust; construction of thermal reactors
	Ignition Timing
F02P 5/00	Advancing or retarding ignition; control thereafter
	Devices for fuel heating, reforming, or activation (FHR)
F02M 27/00	Apparatus for treating combustion-air, fuel, or fuel-air mixture, by catalysts, electric means, magnetism, rays, sonic waves or the like
F02M 31/02-18	Apparatus for thermally treating combustion-air, fuel, or fuel-air mixture

Notes: These IPC codes have been obtained using the following references: Dechezleprêtre et al. (2015), Hascic et al. (2009), Vollebergh (2010)

Table B3: Application and Domestic Countries of Firms in the Sample

Application Country/ Region	Percent of Patents	Domestic Country	Percent of Patents
Austria	6.24	Argentina	0.94
Australia	1.16	Austria	0.03
Bulgaria	0.04	Australia	0.29
Brazil	l 0.2	Bosnia and Herzegovina	0.01
Canada	1.37	Belgium	0.1
Switzerland	0.08	Brazil	4.95
China	23.6	Canada	4.44
Czech Republic	0.2	Switzerland	0.02
Germany	9.35	China	3.71
Denmark	0.72	Czech Republic	0.08
Eurasian Patent Office	0.14	Germany	0.57
Egypt	0.03	Estonia	0.01
European Patent Office	12.06	Spain	0.52
Spain	3.96	France	0.39
Finland	0.25	Great Britain	1
France	3.56	Hong Kong	0.04
Great Britain	1.13	Hungary	0.07
Greece	0.05	Indonesia	0.01
Croatia	0.01	India	0.1
Hungary	0.05	Iran	0.01
Italy	0.34	Italy	0.18
Japan	10.53	Japan	2.45
South Korea	3.89	South Korea	0.76
Mexico	0.04	Morocco	0.01
Malaysia	0.55	Mexico	8.35
Netherlands	0.05	Malaysia	0.29
Norway	0.12	Netherlands	0.03
New Zealand	0.04	Philippines	0.04
Poland	0.18	Pakistan	0.05
Portugal	0.35	Poland	0.07
Russia	0.7	Portugal	0.03
Sweden	0.23	Romania	0.05
Slovakia	0.02	Russia	0.58
Turkey	0.01	Sweden	0.01
Taiwan	1.1	Slovakia	0.08
United Arab Emirates	0.1	Thailand	0.29
USA	17.55	Turkey	0.03
		Taiwan	0.05
		United Arab Emirates	0.01
		USA	68.16
		South Africa	0.41

Notes: Observations where a positive number of patents are granted are used for calculating these statistics (a total of 15336 observations are used).

Table B4: Regression Results for Suppliers Assuming Different Durations of Supplier-OEM Relationship: Poisson Estimation

Duration	3 years				5 years				10 years			
Dep. Var.: Number of clean patents granted to firm i in year t	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	All	Tier 1	Tier 2	Tier 3	All	Tier 1	Tier 2	Tier 3	All	Tier 1	Tier 2	Tier 3
OEM Regulation	-0.052***	-0.051***	-0.029	-0.173***	-0.045***	-0.041***	-0.028	-0.129***	-0.062***	-0.042***	-0.003	-0.124***
	(0.016)	(0.011)	(0.045)	(0.048)	(0.018)	(0.012)	(0.042)	(0.048)	(0.008)	(0.004)	(0.013)	(0.040)
Regulatory Gap (OEM- Inventor)	-0.035**	-0.038***	-0.019	-0.016	-0.045***	-0.020**	-0.042	0.010	-0.064***	-0.010***	-0.018	-0.041
	(0.016)	(0.011)	(0.045)	(0.048)	(0.018)	(0.011)	(0.042)	(0.041)	(0.008)	(0.002)	(0.012)	(0.027)
Domestic Country Regulation	0.055***	0.060***	0.048	0.233***	0.039**	0.016	0.032	0.071**	0.053***	0.002	0.473	0.073***
	(0.016)	(0.011)	(0.045)	(0.079)	(0.018)	(0.011)	(0.037)	(0.041)	(0.008)	(0.003)	(1.074)	(0.030)
Domestic Country Patent Stock	0.976***	0.001***	0.001***	0.882**	0.903***	0.708**	0.656***	-0.317	0.314***	0.316***	0.646***	0.273
	(0.110)	(0.0001)	(0.0003)	(0.044)	(0.390)	(0.380)	(0.161)	(2.847)	(0.056)	(0.056)	(0.097)	(0.218)
Patent Stock Summed Over Recipient Countries	-0.859***	-0.862***	-0.202***	-0.155*	-0.297*	-0.181	-0.362***	-0.880	-0.166***	-0.142	-0.128***	-0.119***
	(0.171)	(0.176)	(0.050)	(0.089)	(0.182)	(0.180)	(0.047)	(0.615)	(0.013)	(0.013)	(0.022)	(0.040)
Observations	7215	7215	1431	694	15603	14783	2990	1348	44666	42556	8129	3489

Notes: All specifications include firm fixed effects, year fixed effects, and application country fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported.

Table B5: Regression Results (Using Patents Filed by Firm in Each Application Country as Dependent Variable): Poisson Estimation

Dep. Var.: Number of clean patents granted to firm i in year t	(1) All	(2) Tier 1	(3) Tier 2	(4) Tier 3
OEM Regulation	-0.036***	-0.016***	-0.020*	-0.051**
	(0.006)	(0.003)	(0.012)	(0.027)
Regulatory Gap (OEM- Domestic)	-0.036***	-0.014***	-0.016	-0.017
	(0.006)	(0.003)	(0.011)	(0.026)
Domestic Country Regulation	0.018***	-0.004	0.009	0.044
	(0.006)	(0.003)	(0.010)	(0.028)
Domestic Country Patent Stock	0.868***	0.870***	0.820	0.462***
	(0.047)	(0.050)	(0.100)	(0.182)
Patent Stock Summed Over Recipient Countries	-0.263***	-0.263***	0.227	-0.159
	(0.058)	(0.056)	(0.774)	(1.260)
Observations	60354	57440	11435	4966

Notes: All specifications include firm-by-application country fixed effects, and year fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported.

Table B6: Regression Results for the Suppliers (Using an Alternative Definition of Regulation): Poisson Estimation

Dep. Var.: Number of clean patents granted to firm i in year t	(1) All	(2) Tier 1	(3) Tier 2	(4) Tier 3
OEM Regulation (Maximum)	0.017*	-0.001	-0.052***	-0.067**
	(0.009)	(0.003)	(0.016)	(0.031)
Regulatory Gap (OEM- Domestic)	-0.043***	-0.004**	0.006	-0.057**
	(0.009)	(0.002)	(0.013)	(0.029)
Domestic Country Regulation	0.044***	-0.006***	-0.021	0.072***
	(0.010)	(0.003)	(0.014)	(0.032)
Domestic Country Patent Stock	0.107***	0.421***	0.807***	0.341*
	(0.004)	(0.060)	(0.090)	(0.208)
Patent Stock Summed Over Recipient Countries	-0.360	-0.486***	0.228	-0.376***
	(0.045)	(0.048)	(0.488)	(0.165)
Observations	31290	60121	12015	5193

Notes: All specifications include firm fixed effects, year fixed effects, and application country fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported.

Table B7: Regression Results for the Suppliers (Using Second Lag of Emission Standard): Poisson Estimation

Dep. Var.: Number of clean patents granted to firm i in year t	(1) All	(2) Tier 1	(3) Tier 2	(4) Tier 3
OEM Regulation	-0.008***	-0.357	-0.006***	-0.004***
	(0.003)	(0.241)	(0.0004)	(0.0006)
Regulatory Gap (OEM- Domestic)	-0.009***	-0.134***	0.006***	-0.888
	(0.003)	(0.026)	(0.0004)	(8.163)
Domestic Country Regulation	-0.003	-0.013***	-0.018***	-0.013***
	(0.004)	(0.002)	(0.002)	(0.002)
Domestic Country Patent Stock	0.394***	0.493***	0.494***	0.487***
	(0.058)	(0.051)	(0.052)	(0.051)
Patent Stock Summed Over Recipient Countries	-0.151***	-0.142***	-0.135***	-0.140***
	(0.014)	(0.014)	(0.013)	(0.013)
Observations	57328	60934	60934	60934

Notes: All specifications include firm fixed effects, year fixed effects, and application country fixed effects. Robust standard errors are reported. *,** and *** respectively denote significance at 10%, 5% and 1% levels. The coefficients of the constant are not reported.