When Strengthening Environmental Regulation Reduces Green Innovation: Theory and Evidence from the Auto Industry

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Abstract

It is commonly believed that strengthening environmental standards increases green innovation. We develop a model and produce empirical evidence which partly disconfirm this view. The model predicts that regulatory change has opposite impacts on innovation when the country is a regulatory leader or a country adopting a standard previously introduced elsewhere. The analysis of panel data from the auto industry from 1992 to 2007 confirms these predictions. We find that regulatory leadership increases innovation whereas innovation falls when the country is a regulatory follower.

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1 Introduction

It is commonly expected that strengthening environmental regulation boosts green innovation. This conventional wisdom relies on a simple theoretical reasoning: Complying with a stricter regulation generates new costs, which spur innovation efforts to reduce them. Since the 1990s, many empirical works have found results in line with this argument (e.g., Aghion et al. 2014, Jaffe and Palmer 1997; Brunnermeier and Cohen 2003; Newell et al. 1999; Popp 2002; Crabb and Johnson 2010; Johnstone et al. 2010).

We develop a simple dynamic model of environmental regulation in the auto industry which partly disconfirms this view. It predicts an ambiguous effect on innovation and stresses the importance of the timing of regulatory change. More specifically, the impact of regulation is totally different when the country is a regulatory leader or a country which adopts a standard previously introduced elsewhere. Empirical evidence is consistent with these insights. Using panel data from the auto industry that includes 72 countries from 1992 to 2007, we find that regulatory leadership increases innovation whereas innovation falls when the country is a follower.

To explain these results, one should briefly present the role of emission standards in the auto industry. Standards that set limits for exhaust emissions of new vehicles exist in most countries (e.g., the European Union, Japan, Korea, China, and the US) and are regularly tightened. For example, the so-called "Euro 1" standard was implemented in the European Union in July 1992 and mandated a limit value of 2.72 g/km for CO emissions. It was then substituted by the "Euro 2" standard in January 1996 which lowered the limit value to 1.0 g/km, followed by "Euro 3" in 2000... Additional revisions were introduced in the 2000s and the current standard is "Euro 6" which requires emitting less than 0.5 g/km since 2014. Importantly for our analysis, regulatory strictness is comparable across countries as they deal with the same pollutants (CO, particulate matters, NOx...). It is then possible to rank the countries with some being regulatory leaders and others being followers. For instance, our data show that the US tended to lead the regulatory race in the 1990s and in the late 2000s whereas the European Union and Japan had stricter regulation between these two periods (see also Dechezleprêtre et al., 2015).

Our result that the dynamics of innovation depends on whether regulation is changed by a country leading the regulatory race or by followers is driven by two crucial assumptions that are likely to be valid in many industries and for many environmental regulations. The first is that innovation is standard-specific. We mean here that a given R&D project only reduces the cost to comply with a specific standard. It neither helps to comply with older standard nor with the future ones. The second is that the vehicles are traded internationally. As a result, automakers do not only respond to regulatory changes that occur in the domestic market, but also to changes in the foreign markets.

These two characteristics imply very different adjustments when a leader introduces a new standard compared to what happens when a follower catches up. When a leader tightens its regulation, innovators start developing a new set of technologies, but they also continue to improve the older ones as earlier standards remain in place abroad. This may induce more innovation for several reasons. To begin with, innovators innovate more when a technology is new because, assuming that the marginal impact of research expenditures on compliance cost is decreasing, starting with a new technology means higher marginal innovation benefits. The innovation benefit is also high because the lifetime of the new standard is longer than that of the older standards which remain in place. Compliance cost reductions induced by innovation will thus persist over a longer period. But, at the same time, innovators reduce innovation related to the previous standard as its residual lifetime gets shorter. The overall effect on innovation is thus indeterminate in general.

The fact that we see opposite patterns when a follower adopts the standard is not that surprising as it corresponds to the symmetric case when innovators stop innovating on the old technology and concentrate their efforts on the new one.

As outlined above, existing works generally find a positive impact on innovation. Is it possible to reconcile these results with our findings? Some of these studies are not directly comparable as they deal with the impact of energy prices on innovation whereas we analyze product regulatory standards (Aghion et al. 2014; Newell et al. 1999; Popp 2002). Others implicitly examine the impact of regulation constraining emissions at the production stage as they use the level of pollution abatement and control expenditure as a proxy for regulatory strictness (Jaffe and Palmer 1997; Brunnermeier and Cohen 2003). In this paper, we examine standards that concern products (which can then be traded internationally). Others like Johnstone et al. (2010) use cross-country data and analyze regulations that concern traded goods, but they look at the *average* impact of regulation on innovation, without paying attention to the differences between leaders and laggards.

Our results also echo the well-known argument made by Porter and van der Linde (1995) on the relationships between environmental regulation and competitiveness. In their paper, an important claim is that, although a country's regulatory leadership induces higher costs in the short run for domestic firms, it also fosters green innovation which could generate economic benefits in the long run by giving a competitive advantage over foreign firms that will be constrained by the same regulation later on. Our analysis yields some insights in line with the first part of their story: regulatory leadership induces more innovation. But we do not investigate the second part, that is, whether additional innovation induces better economic performance.

The rest of this paper is structured as follows. We briefly present the organization of the automotive industry in the following section. In Section 3, we present the model. Section 4 describes the data that are used in the empirical analysis. The estimation framework and the econometric results are presented in Sections 5 and 6. Section 7 summarizes our findings.

2 The automobile sector

The automobile sector is a transnational assembly industry wherein components, systems and modules are produced and assembled across a number of different countries (Dicken 2011). At the apex of what Pavlínekt and Źenka (2009) characterise as a producer-driven network are large assembly firms (i.e. final producers) which exercise considerable power and control over the supply chain. A relatively small number of European, Japanese, US and South Korean multinational final producers dominate the industry worldwide. These firms tend to organise production on a regional basis in order to supply large market centres – with a trend towards producers locating assembly plants in developing and transition economies with lower production costs (Sturgeon and Van Biesebroeck 2010). The past decade has also witnessed the dramatic growth of Chinese manufacturers, many of them working with various foreign equity partners, or else relying significantly on foreign technology acquisitions through licencing or outward FDI (Chin 2010). Indeed, along with other industrialising developing countries such as Brazil, India and South Africa, China has accounted for a rapidly rising share of worldwide automotive production since the 1990s (Bailey et al. 2010; Kumaraswamy et al. 2012).

Another pivotal set of firms in the automobile industry are the so-called tier 0.5 and tier 1 suppliers which have assumed an increasingly important role in manufacturing and, moreover, innovating key components, modules and systems for final producers (Cabigiosu et al. 2013). The majority of lead suppliers are themselves multinationals and often "follow" final producers into foreign markets where they operate (Dicken 2011). Tier 0.5 and 1 firms also play a co-ordinating role with regards to large numbers of (often smaller and domestic) tier 2 and 3 suppliers. Bulky and/or specialised components tend to be produced close to final assembly plants, while others are sourced globally, including generic components which can be readily transported (Sturgeon and Van Biesebroeck 2010).

Turning specifically to environmental technologies, which are a major focus of ongoing innovative efforts in the automotive industry (Lee and Berente

2013), the picture is very similar. Both final producers and lead suppliers innovate (and manufacture) ESTs. In terms of the former, large multinationals such as GM, Toyota, Volkswagen and Renault are key actors, spending significant amounts on R&D involved in reducing tail-pipe emissions (Mondt 2000; Oltra and Saint Jean 2009; Haščič and Johnstone 2011b; OECD 2011; Berggren and Magnusson 2012). Indeed, to the extent that compliance with more stringent emissions regulations cannot simply be achieved by installing after-treatment technologies, environmental considerations have increasingly become integral to transnationals' powertrain (i.e. base-engine) design and engineering activities. Smaller, domestic producers – including those in emerging economies – have also been active in innovating ESTs, although they are more likely to rely on acquiring emission-relevant technology from transnational vehicle manufacturers or external suppliers (Perkins 2007; Chin 2010).

The importance of suppliers in innovating automotive ESTs is indicative of the wider tendency of final producers to contract-out the design (and production) of major components, systems and modules to external firms. Tier 0.5 and 1 firms such as Delphi Automotive which supply a range of product lines (e.g. safety electronics, climate control systems, etc.) are therefore also involved in emissions control technology. Additionally, the importance of external suppliers in ESTs has arisen because many of the competencies required for improving the environmental performance of vehicles has resided in a range of other sectors such as chemicals and electronics (Geffen and Rothenberg 2000; Lee et al. 2011; Hall and Kerr 2003). In the case of catalytic converters, for example, chemical firms such as Johnson Matthey have played a crucial role in providing specialist technological expertise and capabilities to the automotive sector required to meet ambitious emission standards (Mondt 2000; Tao et al. 2010).

The vast bulk of new automotive ESTs are developed in a handful of industrialised economies (Oltra and Saint Jean 2009; Haščič and Johnstone 2011b). Germany, Japan and the US account for the majority of innovative output, with South Korea, France and the UK also significant sources of innovation. A number of factors explain this concentration. One is that R&D facilities – both of final producers and suppliers involved in ESTs and other automotive technologies – have tended to develop close to the traditional headquarter countries of automobile majors. Moreover, taking advantage of accumulated knowledge capabilities in established clusters and a desire to protect technological knowledge, automobile majors and leading suppliers have continued to base R&D activities in these locations, even as they have significantly expanded their operations elsewhere (Pavlínek 2012; Sturgeon and Van Biesebroeck 2010; The Economist 2013). Another factor which has contributed to the dominance of certain countries in innovating ESTs is environmental regulation. The US historically led the way in the adoption of the most stringent emission standards worldwide during the 1970s and 1980s (Gerard and Lave 2005; Bauner 2007). This stimulated the domestic innovation of ESTs – as well as innovation in economies for which the US was a major export market (e.g. Germany, Japan, Sweden and the UK) (Boehmer-Christiansen and Weidner 1995; Tao et al. 2010). In the 1990s and 2000s, these latter countries themselves became regulatory frontrunners, with innovative activity in ESTs building on earlier efforts to achieve domestic regulatory compliance.

However, notwithstanding the dominance of certain developed countries, there is a growing trend towards innovation of ESTs outside of this historic "core" – including larger rapidly industrialising economies. In part, this stems from the strategic decision of transnational producers and major suppliers to set up local design and engineering centres close to major markets where they have significant manufacturing/assembly facilities. Additionally, it is a product of growing R&D efforts by domestic firms, including domestic suppliers. Much of this innovative activity is incremental, taking the form of within-component/system innovation directed towards improving and adjusting powertrain systems to suit particular domestic market characteristics, such as fuel quality or consumer preferences (Chin 2010; Sturgeon and Van Biesebroeck 2010; Pavlínek 2012). More recently, however, evidence points to increased innovative activity outside of the traditional inventive core oriented towards the development of new emissions-relevant products and designs (e.g. see Lema et al. 2012).

Cross-border technology transfer is a key feature of the automotive industry. This takes place as a result of "internal" trade, as technologies flow amongst different parts of multinational producers' and suppliers' regional (and, to a lesser extent, global) networks, as well as between different firms which engage in technology-sharing joint ventures and alliances (Bailey et al. 2013; The Economist, 2013). In fact, because of the importance of economies of scale for competitiveness, manufacturers characteristically "share" components, systems, platforms and designs across multiple markets in which they operate. Additionally, technology transfer takes place as automotive technology innovated in one country is sold to firms or final consumers in another country, both in embodied form (via imports of components, completely built up vehicles, etc.) and disembodied form (via technology licences, consultancy services, etc.) (Mikler 2009; Kumaraswamy et al. 2012).

An important component of these transfers is ESTs. Many technologies involved in reducing tail-pipe emissions are R&D-intensive, implying that innovators will want to amortise costs across large numbers of units. Moreover, to the extent that there are significant economies of scale in manufacturing base-engine and after-treatment systems, modules and components, there are strong economic incentives to use similar technologies for products manufactured and/or sold in different markets (Bauner 2007; The Economist 2013). Indeed, combined with intense price-based competition, these economic realities mean that final producers invariably use the same core base-engine technology across multiple countries where they sell a particular model (Perkins 2007).

Yet the flip side of price competition is that emissions relevant technology installed in vehicles will often be "tailored" to conditions in the markets in which they are sold. A critical factor in this respect is the stringency of domestic emissions regulations. An important reason why transnational vehicle producers do not simply deploy the same base-engine configuration and after-treatment technology, matching the highest standards globally, is that more sophisticated ESTs required to achieve lower levels of emissions are more expensive. All else equal, a vehicle capable of achieving more stringent emission standards will be more costly to produce, and therefore more expensive for final consumers. Therefore, vehicle manufacturers characteristically "engineer" vehicles according to domestic standards in any one particular market in which they are sold, even though variants of the same model may be sold in other markets configured to higher/lower emission standards (Bauner 2007; Gallagher 2006; Perkins 2007).

Differences in environmental regulatory standards are not the only reason for variations in vehicle technology across markets. Another one is local consumer preferences, in terms of attributes such as fuel efficiency or acceleration, although significant modification of vehicles to suit these preferences is only viable for larger markets (Perkins 2007; Chin 2010; The Economist 2013). Purchasing power is a further factor in that consumers in certain markets are better able to afford more advanced, costly vehicle technology than others. Furthermore, the domestic availability of high quality fuel is also a potential influence on technological choice to the extent that advanced base-engine and after-treatment technology requires a certain grade of petrol/diesel in order to function correctly. Indeed, the above considerations are a factor underpinning the strategic decision of vehicle manufacturers to pursue regional production strategies, deploying particular model variants in sets of markets with similar characteristics (Dicken 2011; Sturgeon and Van Biesebroeck 2010).

One consequence of these strategies is that the most advanced ESTs, the majority of which will have been recently innovated in high-regulating, developed economies, are destined at other high-regulating, developed economies. This is because such technologies will be better matched to environmental regulatory requirements, customer preferences and purchasing power. Furthermore, some producers and suppliers may be reluctant to transfer the very latest ESTs to certain emerging markets/developing countries owing to concerns about the loss of intellectual property (Gallagher 2006). Conversely, ESTs recently-innovated in lower-regulating countries are more likely to go to other lower-regulating countries. These inventing lower-regulating countries are predominantly emerging or transitional economies with significant car production/components manufacturing capacity. Much of the inventive effort here will have gone into incremental improvements in order to make the technology better suited to requirements domestically, as well as other emerging/transitional export markets (Bauner 2007).

There will be plenty of exceptions. Some ESTs (e.g. sensors for electronically-controlled fuel injection) innovated in lower-regulating countries will be oriented towards meeting requirements in foreign higher-regulating ones. The most advanced, recently-innovated ESTs are sometimes transferred from high-regulating innovator countries to lower-regulating countries where they are manufactured or assembled for export to high-regulating markets. Furthermore, vehicles sold in lower-regulating markets will inevitably incorporate technology (e.g. engine blocks) originally innovated in high-regulating economies in the past, although modified over time to suit different requirements. Additionally, technology transfer may take place from high-regulating to low-regulating countries when engineering consultants located in the former assist firms with meeting regulatory standards (Chin 2010; Sturgeon and Van Biesebroeck 2010). However, it is our contention that the predominant pattern is for recently innovated ESTs to flow from countries which have similar emissions standards, rather than countries with dissimilar ones.

The automobile sector offers several analytical advantages as a test case for our hypotheses. First, a large number of countries have adopted tailpipe emission standards, with significant cross-national variations in regulatory stringency over the period of our study (Beise and Rennings 2005). The sector therefore lends itself to testing our hypotheses focusing on regulatory frontrunners versus followers. Second, complying with tailpipe emission standards is largely achieved through base-engine and after-treatment technologies, allowing us to examine the degree to which regulation drives innovation through the patent system (Haščič et al. 2009; Perkins 2007; Gallagher 2006; Lee and Berente 2013). A third salient characteristic is that patenting is a key feature of the automobile sector. This reflects the importance of protecting intellectual property from competitors as well as the licencing of technologies (Kumaraswamy et al. 2012) and the widespread flow of technologies among final producers and suppliers between different parts of their regional and/or global networks.

3 The model

3.1 Assumptions

We propose a model in discrete time with two symmetric countries that only differ in the timing of policy change. Consider a particular period T. We assume that one of the country indexed L (for leader) shifts from a standard $s-1$ to a stricter standard s at time T that it will keep in place until $T+2$. The other country indexed F follows by adopting the same standard s at time $T+1$ for two periods. Then country L adopts a new standard $s+1$ at that $T+2$, and so on and so forth.

In each country, a firm produces cars that are sold in the domestic and foreign markets. Indices L and F will also identify the two automakers. A vehicle which complies with the new standard is more costly to produce than a vehicle complying with the previous one. More specifically, we assume complying with the standard increases the unit manufacturing cost by an amount C°. This cost can be reduced with innovation. More specifically, firm L's compliance cost after innovation is $C_t = C^{\circ} - \sum_{k=0}^{t} b(Q_{t-k}^s)$ where Q_t^s is some measure of innovation output related to standard s made by firm L in period t. Let $\bar{C}_t$ denote the same function for firm F. In the empirical part of the paper, we will use patents to construct a proxy of Q_t^s and $\bar{Q}_t^s$. We will come back in detail on this when describing the empirical strategy. We impose that $b(0) = 0$, $b' > 0$ and that innovation returns are decreasing, $b'' < 0$. Moreover, we impose that C° is sufficiently high such that $b < C^{\circ}$, meaning that innovation cannot cancel the compliance cost even with huge innovation efforts.

Following Blundell et al. (1995, 2002) and others, we suppose that the innovation output is equal to the knowledge stock. We adopt the standard assumption that the stock is a weighted sum of present and past research expenditures. The expressions for firms L and F's innovation outputs are respectively:

$$q_t^s = \sum_{k=0}^{t} \mu^k r_{t-k}^s \tag{1}$$

$$\bar{q}_t^s = \sum_{k=0}^{t} \mu^k \bar{r}_{t-k}^s \tag{2}$$

where r^s_{t-k} is the level of R&D expenditures at time $t-k$ made by the firm L. $\bar{r}^s_t$ is firm $F's$ research expenditures.[1,2] The parameter μ captures knowledge obsolescence ($\mu \leq 1$). Next, we introduce the crucial hypothesis that innovation is specific to each standard. We mean here that q^s_t and $\bar{q}^s_t$ only lower the cost to comply with standard s. As a result, innovation is zero before T as the firms have no reason to do research in advance ($r^s_t = 0$ and thus $q^s_t = 0$ if $t < T$). Symmetrically, once country F has shifted to the next standard at $t \geq T+3$, we also have $r^s_t = 0$. What matters is simply the innovation made between T and $T+2$.

The fact that innovation is standard-specific simplifies the analysis in two ways. First, innovation decisions for each standard are totally independent and can thus be analyzed separately. Second, the process is stationary: what happens in equilibrium at time T when s is in place in country L is exactly what will happen for standard $s+1$ at $T+2$; the same is true for s and $s+1$ at $T+1$ and $T+3$, and so on. We can thus entirely focus the analysis on the sequence between T and $T+2$.

Turning next to the description of the car market, we consider a scenario where the market is global so that each firm sells $N/2$ cars at home and $N/2$ abroad. Sales are constant over time, meaning that policy changes do not affect market shares. They only affect unit manufacturing costs through the

[1] We could assume the existence of knowledge spillovers, for instance by considering that the stock of knowledge is the weighted sum of $r^s_t + \sigma \bar{r}^s_t$ where σ captures the amount of research efforts by firm F which is accessible to firm L. This is useless for our purpose as spillovers only affect the level of research expenditures in equilibrium, not that of the knowledge stocks.

[2] Under our assumptions, the research process is deterministic in the sense that any expenditure always reduces the compliance cost. Adding uncertainty on the impact of r on C would not alter the results.

compliance costs. This will imply that innovation benefits are proportional to sales. More fundamentally, we here rule out strategic effects in the market. As the value of N is qualitatively irrelevant, we assume from now on that $N = 1$ to simplify notations.

We can derive the market sizes for cars that comply with standard s at different dates:

- At time T when the standard has only been adopted in country L, the market size is $1/2$ for firm L and firm F.
- At time $T + 1$ when the standard is in place in both countries, the market size is 1 for both firms.
- At time $T + 2$ when the leading country has shifted to the stricter standard $s + 1$, the market size is $1/2$ for L and F.

3.2 Equilibrium analysis

We can now analyze firm L's innovation decision with respect to standard s. To ease notations, we ignore the standard index at this stage of the analysis. It chooses the flow of research expenditures r_T, r_{T+1}, and r_{T+2} that maximizes the discounted benefit of innovation:

$$\Gamma \equiv \frac{1}{2}b(q_T)+\delta\left[b(q_T)+b(q_{T+1})\right]+\frac{1}{2}\delta^2\left[b(q_T)+b(q_{T+1})+b(q_{T+2})\right]-\sum_{k=0}^{2}\delta^k r_{T+k}$$

where δ is the discount factor ($0 < \delta < 1$). Assuming interior solutions, the research expenditures in equilibrium satisfy the three following first-order conditions:

$$\frac{\partial\Gamma}{\partial r_T} = \left[\frac{1}{2} + \delta + \frac{1}{2}\delta^2\right] \cdot b'(q_T) + (\delta\mu)\left[1 + \frac{1}{2}\delta\right] \cdot b'(q_{T+1}) + \frac{1}{2}(\delta\mu)^2 \cdot b'(q_{T+2}) - 1 = 0 \tag{3}$$

$$\frac{\partial\Gamma}{\partial r_{T+1}} = \left[1 + \frac{1}{2}\delta\right] \cdot b'(q_{T+1}) + \frac{1}{2}\delta\mu \cdot b'(q_{T+2}) - 1 = 0 \tag{4}$$

$$\frac{\partial\Gamma}{\partial r_{T+2}} = \frac{1}{2}b'(q_{T+2}) - 1 = 0 \tag{5}$$

Note that Γ is concave in all its arguments (as b is concave and research costs are linear). We just need to introduce the innocuous assumption that $\frac{\partial\Gamma}{\partial r_{T+2}} > 0$ in the case where $r_{T+2} = 0$, which is equivalent $\frac{1}{2}b'(0) - 1 > 0$, for ensuring the existence and uniqueness of interior solutions. This hypothesis essentially means that the marginal benefit of innovation is always sufficiently high to induce a strictly positive level of research expenditures in equilibrium.

Substituting (5) in (4) and then in (5) yields that

$$b'(q_T) = \frac{1 - \delta\mu}{\frac{1}{2} + \delta + \frac{1}{2}\delta^2} \tag{6}$$

$$b'(q_{T+1}) = \frac{1 - \delta\mu}{1 + \frac{1}{2}\delta} \tag{7}$$

$$b'(q_{T+2}) = 2 \tag{8}$$

The level of innovation of firm F is the same at the firm also maximizes the function Γ. We are now able to rank the level of per-period innovation outputs.

Lemma 1 *1)* $q_T > q_{T+1}$ *and* $\bar{q}_T > \bar{q}_{T+1}$ *if* $\delta > \frac{1}{2}\sqrt{5} - \frac{1}{2}$*; 2)* $q_{T+1} > q_{T+2}$ *and*

$\bar{q}_{T+1} > \bar{q}_{T+2}$; 3) $q_T > q_{T+2}$ and $\bar{q}_T > \bar{q}_{T+2}$.

Proof. 1) $q_T > q_{T+1}$ direcly follow from the concavity of b and the fact that $b'(q_T) < b'(q_{T+1}) \Leftrightarrow \delta > \frac{1}{2}\sqrt{5} - \frac{1}{2}$. 2) Because $2 > \frac{1-\delta\mu}{1+\frac{1}{2}\delta}$; 3) Because $\frac{1-\delta\mu}{\frac{1}{2}+\delta+\frac{1}{2}\delta^2} < 2$. ■

These results are driven by several factors. An obvious ingredient is discounting which creates incentives to delay innovation. Another is the evolution of market size through time. In particular the largest market is observed at time $T+1$ when both countries implement s while market at T is larger than at $T+2$ for the leader. The term $\delta\mu$ exhibits a third driver: the fact that contemporaneous research increases the stock of knowledge, and thus future innovation. This creates incentives to do more research in the initial periods T and $T+1$. In contrast, the incentive disappears at $T+2$ as the future stock becomes useless at the end of the period. A last factor also promotes earlier innovation: the fact that the innovation benefit persists in future periods.

These factors lead q_{T+2} to be lower than innovation in the previous periods because the market for innovation is the smallest and the future innovation benefit are zero. The ambiguity of the ranking between q_T and q_{T+1} results from the tradeoff between discounting - a high discount factor δ give more weight to future benefits and thus foster earlier innovation - and market size which is larger in period $T+2$.

3.3 Total innovation

Until now we have only characterized the equilibrium levels of innovation related to standard s. But this standard co-exists with standard $s-1$ in period T and with standard $s+1$ in period $T+2$. Innovation efforts to comply with the other standards at these two dates thus need to be integrated in the calculation of total innovation. Stationarity considerably eases this analysis. To begin with, we only need to consider two periods: T when the countries implement two different standards and $T+1$ when they do the same. $T+2$ is equivalent to T except that it describes the next wave of regulation.

Let Q_t denote total innovation of firm L at time t. We are primarily interested in the sign of $\Delta Q_T = Q_T - Q_{T-1}$.That is, whether innovation increases when country L introduces a stricter standard. We have $Q_T = q_T^s + q_T^{s-1}$. Stationarity then implies that $q_T^{s-1} = q_{T+2}^s$ while $Q_{T+1} \equiv q_{T+1}^s$. Hence, we need to look at the sign of

$$\Delta Q_T = q_T + q_{T+2} - q_{T+1}$$

where q_T, q_{T+2} and q_{T+1} are implicitly defined by (3), (4), and (5) that we rewrite here for convenience:

$$\begin{aligned} b'(q_T) &= \frac{1-\delta\mu}{\frac{1}{2}+\delta+\frac{1}{2}\delta^2} \\ b'(q_{T+1}) &= \frac{1-\delta\mu}{1+\frac{1}{2}\delta} \\ b'(q_{T+2}) &= 2 \end{aligned}$$

Given Lemma 1, it is straightforward that $\Delta Q_T > 0$ if $\delta > \frac{1}{2}\sqrt{5} - \frac{1}{2}$ as we have

$q_T > q_{T+1}$ in this case. The analysis is more complicated when $\delta < \frac{1}{2}\sqrt{5} - \frac{1}{2}$. The important point is that we can have $\Delta Q_T < 0$. It is for instance true when b is a quadratic function and $b'(0) = 2$.[3]

The point is then to investigate how parameters' value influence this difference. To facilitate the comparison we impose from now on that:

Assumption: b **is a quadratic function such that** $b'(q) = b'(0) - aq$ **with** $a > 0$.

Under this assumption, the sign of ΔQ_T is that of

$$\begin{aligned}\Omega(\alpha, \delta, \mu) &= b'(0) - b'(q_{T+2}) - b'(q_T) + b'(q_{T+1}) \\ &= b'(0) - 2 + \frac{1 - \delta\mu}{1 + \frac{1}{2}\delta} - \frac{1 - \delta\mu}{\frac{1}{2} + \delta + \frac{1}{2}\delta^2}\end{aligned}$$

In that case, it is immediate that Ω increases with $b'(0)$. It also increases with μ in the case where the sign of Ω is ambiguous ($\delta < \frac{1}{2}\sqrt{5} - \frac{1}{2}$). Then we have

$$\begin{aligned}\frac{d\Omega}{d\delta} &= \frac{\mu}{1 - \delta\mu}\left(b'(q_T) - b'(q_{T+1})\right) \\ &\quad + (1 - \delta\mu)\left((1 + \delta)\left[b'(q_T)\right]^2 - \frac{1}{2}\left[b'(q_{T+1})\right]^2\right)\end{aligned}$$

which is positive when $\delta < \frac{1}{2}\sqrt{5} - \frac{1}{2}$ as $b'(q_T) > b'(q_{T+1})$. Finally, we have:

$$\frac{d\Omega}{d\alpha} = (1 - \mu\delta)\left(\frac{\left(1 - \delta^2\right)}{\left(\frac{1}{2} + \delta + \frac{1}{2}\delta^2\right)^2} + \frac{\delta}{\left(1 + \frac{1}{2}\delta\right)^2}\right) - 4$$

[3] $b'(0) = 2$ implies $q_{T+2} = 0$ and thus $\Delta Q_T = q_T - q_{T+1}$ which is negative when $\delta < \frac{1}{2}\sqrt{5} - \frac{1}{2}$.

Simulations then show that it is negative for any δ in the case where $\mu = 0$; which is a sufficient condition for having $\frac{d\Omega}{d\alpha} > 0$.

We are now able to write a first proposition:

Proposition 1 *When country L shifts to a stricter standard, the variation of innovation has an ambiguous sign. It is more likely to be positive when the innovation benefit is high (a high $b'(0)$), when the pace of regulatory change is fast (a high discount factor δ), and when technological obsolescence is limited (a high μ).*

It is always difficult to qualify the degree of likelihood that regulatory change actually raises innovation. But the analysis suggests it is actually high. For instance, it is the case as soon as $\delta > \frac{1}{2}\sqrt{5} - \frac{1}{2} \simeq 0.62$ for any value of μ and $b'(0)$.

Turning next to country F, the reasoning is very similar, but results are in sharp contrast. The most important point is that policy change occurs in period $T+1$ in that country, meaning that the variation of innovation to consider is now $\Delta\bar{Q}_{T+1} = \bar{Q}_{T+1} - \bar{Q}_T$. Then stationarity implies that $\Delta\bar{Q}_{T+1} = \bar{q}_{T+1} - \bar{q}_T - \bar{q}_{T+2}$ and thus $\Delta\bar{Q}_{T+1} = -\Delta Q_T$. Hence

Proposition 2 *When country F shifts to a stricter standard, the sign of the variation of innovation is the opposite of the variation observed when country L strengthens its regulation. As a result, it is more likely to be positive when the innovation benefit is low (a low $b'(0)$), when the pace of regulatory change is slow (a low discount factor δ), and when technological obsolescence is high (a low μ).*

We now develop an empirical analysis to test these predictions.

4 Data

4.1 Automobile emission regulation data

Data for environmental product standards governing maximum permissible levels of tailpipe emissions for pollutants from new (gasoline) automobiles were sourced from a dataset originally constructed by the authors (Perkins and Neumayer 2012). Our analysis covers the period 1992-2009. Countries' regulatory stringency is coded on a scale of 0 to 5. The basis of the classification scheme is the European Union's (EU) "Euro" emission standards which were originally implemented across member states in 1992 (Euro 1) and have subsequently been tightened in a series of incremental steps (Euro 2, 3, etc.). The regulations govern maximum permissible levels of tailpipe emissions for several criteria pollutants (such as CO and NOx) from new passenger car vehicles. While certain member states (e.g. Germany) were active in lobbying for stringent EU-wide emission standards from the outset, the European Commission has subsequently played an important role in driving forward various revisions of the Euro standards.

A significant number of non-EU states which have sought to substantively address passenger car emissions have used the Euro standards as the basis of their own emission standards, including many developing countries, meaning that it is possible to readily code changes in regulatory stringency. Other countries have adopted non-EU standards, most notably Japan and the US, together with a set of countries which have adopted variants of these two major auto producers' standards. In these cases, regulatory stringency was converted to the equivalent Euro standard, see Perkins and Neumayer (2012) for details.

Countries were coded 0 if they had no national emissions standards in place for new vehicles, or if standards were less stringent than the equivalent of Euro 1, during the year in question. Countries where Euro 1 or its equivalent was legally enforceable were coded 1, and so on, with 5 for countries having implemented the equivalent of the Euro 5 standard. As shown in figures 1 and 2, respectively, our sample period is characterised by regulatory tightening in automobile emission standards across both developed (OECD) and developing (non-OECD) countries. As one would expect, developed economies have been regulatory frontrunners, while developing ones have been laggards.

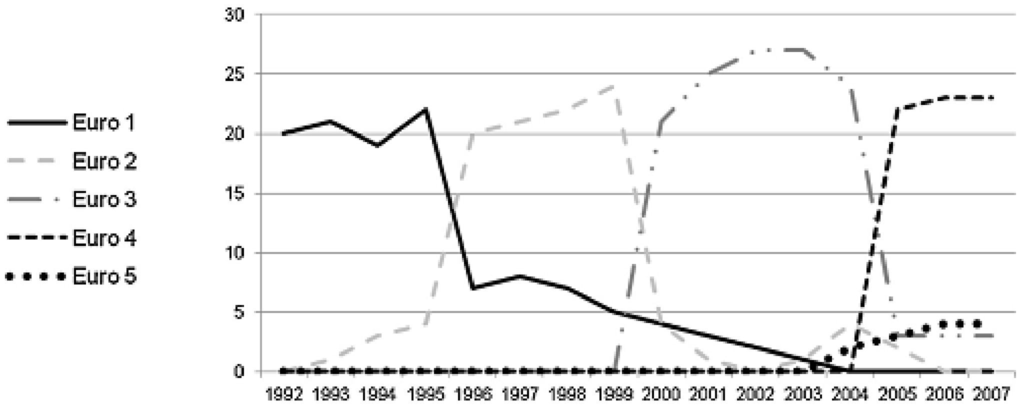

Figure 1 - Number of adopters of Euro equivalent standards in OECD countries 1992 2007

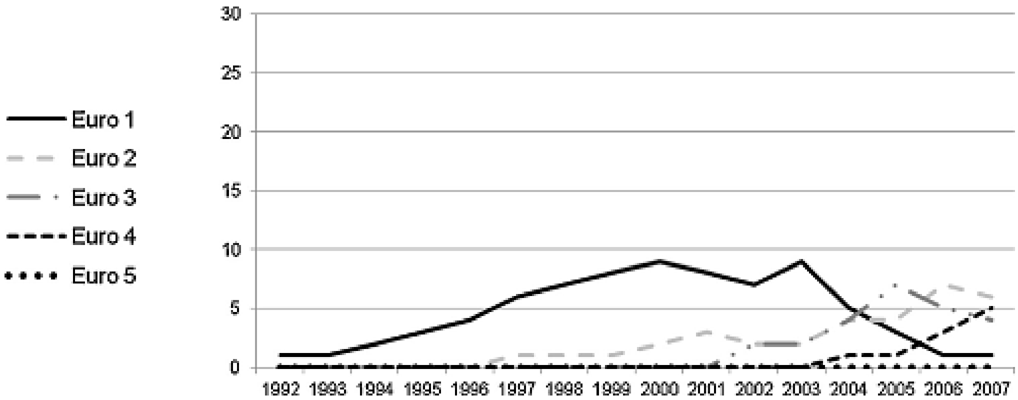

Figure 2 - Number of adopters of Euro equivalent standards in non OECD countries 1992 2007

4.2 Patent data

Our patent data were obtained from the World Patent Statistical Database, otherwise known as PATSTAT, maintained by the European Patent Office (PATSTAT 2013). The PATSTAT database includes over 70 million patent documents filed since the middle of the 19th century in over 80 patent offices in the world. It is the most complete global patent database in the world. Although the whole population of patents ever filed in the world is not included, all major patent offices are featured, and only countries where intellectual protection is very weak (and where as a result patenting is very limited) are not included in the database. Hence, we are confident that our dataset covers the near-population of patents filed in the world covering automobile emissions control technologies. Sampling bias is thus likely to be extremely limited.

We extracted all the patents filed in seven categories of automotive emissions abatement technology: air-fuel ratio devices; fuel injection technologies; catalytic converters and other post-combustion devices; positive crankcase ventilation systems; exhaust gas recirculation valves; on-board diagnostic systems; and oxygen, NOx and temperature sensors. Relevant patent applications were determined using International Patent Classification (IPC) codes identified by Haščič et al. (2009) and Vollebergh (2010). The list of IPC codes used in our analysis is provided in Appendix 1. In our baseline estimation, we pool all technologies together, but in the sensitivity tests we analyse the main ones individually.

Importantly, the same invention may be patented in several countries. This could lead to double-counting of some inventions. However, once patent protection has been requested in one country, subsequent patents covering the same invention in other countries must designate the original patent as their "priority patent". The set of patents covering the same invention in several countries is referred to as a patent family. Our measure of innovation is thus based on counts of patent families. This allows us to avoid issues with double counting.

Every patent includes information about the inventor, including their country of residence. We use this information to determine where each innovation was developed, independently of the patent office in which the patent was filed.[4] If a Canadian researcher working in a US-based lab files a patent, this invention is attributed to the US.[5] Patents are counted by the year of

[4]For 1.4% of the patent applications included in our dataset, the inventor's country of residence is not available. When this information is missing, we simply assume that the inventor's country corresponds to the first patent office in which protection was taken (i.e. the priority office).

[5]Patents with multiple inventors are counted fractionally. For example, if two inventor

the earliest application within the family. Our estimation sample comprises 139,434 patent families developed in 103 countries.

Patent data have been extensively used as a measure of innovation in the recent empirical literature (Popp 2002, 2006; Johnstone et al. 2010; Aghion et al., 2014). The advantages and the limitations of this indicator have been discussed at length in the literature (see Griliches 1990, and OECD 2009 for an overview).

There are several advantages of using patents to measure innovation output. First, they are available at a highly technologically disaggregated level. We can distinguish innovations in the auto industry developed specifically to reduce pollution whereas R&D investments or foreign direct investments cannot be easily disaggregated. Second, patents are recorded for all inventors, while R&D expenditures are not reported for small and medium sized firms. Third, evidence shows that patents are perceived as an effective means of protection against imitation in the automobile sector, something which is not true in all sectors (Cohen et al. 2000).[6]

Using patents as an indicator of innovation is nevertheless not without limitations. To start with, not all inventions are patented. One of the main limitations is that the value of individual patents is highly heterogeneous. To mitigate this problem we present results where our outcome measure focuses on high-value patents that have been filed in at least two countries,

countries are involved in an invention, then each country is counted as one half.

[6]Cohen et al. (2000) conducted a survey questionnaire administered to 1,478 R&D labs in the U.S. manufacturing sector. They rank sectors according to how effective patents are considered as a means of protection against imitation, and find that the top three industries according to this criterion are medical equipment and drugs, special purpose machinery and automobiles.

as opposed to the more expansive category of all patent applications. This method is becoming one of the standard ways in the literature to get rid of the large proportion of patents that are of very low value and tend to be protected in a single country. Another limitation is that, although a patent grants the exclusive right to use a technology in a given country, we do not have any information on whether the technology has actually been used in practice. Yet the high expense of patenting deters the filing for protection in countries where the technology is unlikely to be deployed. In the early 2000s, filing a patent cost around €5,000 in Japan, €10,000 in the US and €30,000 at the European Patent Office (EPO) (Roland Berger 2005). Inventors are therefore unlikely to apply for patent protection in a particular economy unless they are relatively certain of the potential market value for the technology. Indeed, empirical evidence suggests that inventors do not patent widely and indiscriminately, with the average invention only patented in two countries (see Dechezleprêtre et al. 2011).[7]

5 Estimation framework

5.1 Baseline model specification: the effect of regulatory stringency on innovation

The number of new inventions for which inventors seek patent protection is measured by Pit, the share of patents related to pollution control technologies filed by inventors from country i in year t. Using the share of pollution con-

[7] 75 per cent of inventions are patented in only one country.

trol patents allows us to control for time-varying changes in the propensity to patent and thus captures any change in the level of intellectual property protection. Our empirical model is derived from our theoretical model presented above:

$$\ln(P_{it}) = \alpha \cdot CHANGE_{it} + \beta \cdot LEADER_{it} + \gamma \cdot CHANGE_{it} \times LEADER_{it} + X_{it} + \varepsilon_{ijt}$$

Where X_{it} is a vector of control variables, including a full set of country and year fixed effects, and ε_{ijt} is the error term.

Our main parameters of interest are α and γ. α reflects the impact of a change in regulatory stringency on patent filings in follower countries, while γ captures the difference in the impact of a change in regulatory stringency on patent filings between follower and leader countries. $\alpha+\gamma$ in turn captures the impact of a change in regulatory stringency on patent filings in leader countries.

We define $CHANGE_{it}$ to be equal to one for leader and follower countries in the year of an increase in regulatory stringency and in the following year. We define $LEADER_{it}$ in a number of ways, but in our baseline specification $LEADER_{it}$ is equal to one for countries that have the highest level of regulation globally.

Finally, to account for the fact that different levels of regulation might entail different innovation efforts, we include a full set of dummy variables for each level of regulation, from EURO 1 to EURO 5 (the baseline being the absence of regulation).

5.2 Estimation technique and sample

We estimate our empirical equation by ordinary least squares with standard errors clustered at country level. The main advantage of using OLS is that it makes the interpretation of interaction effects straightforward. We add an arbitrary constant to the dependent variable before taking the log (to keep observations where the dependent variable is equal to zero), but also estimate directly in levels, in logs (dropping zeros) and use Poisson-type models as robustness checks.

6 Results

6.1 Main results

Our main estimation results are presented in table 1. Column 1 shows results for all patent applications and column 2 uses only high-value patents as defined above. Consistent with our model, we find that regulatory leaders and followers react differently to a change in regulation. This difference is captured by the coefficient γ on the interaction variable $CHANGE_{it} \times LEADER_{it}$ which is positive and highly statistically significant. More precisely, we find that the effect of a change in regulatory level in follower countries, identified by the coefficient α, is negative. We find that a change in regulatory stringency in a follower country translates into an 8% to 11% drop in inventive activity. This effect, which goes against most of the previous literature, is highly statistically significant. The effect of a change in regulatory level in leader countries is given by the sum of coefficients α and

γ, which is equal to 0.135 for model (1) and 0.089 for model (2). In other words, a change in regulatory stringency in a leader country induces an increase in innovative efforts by 9%-13%. Importantly, this effect is also highly statistically significantly different from 0 (p=0.0232).

To sum up, our empirical model offers considerable support for our theoretical predictions. The reaction of leaders and followers to a change in domestic regulation is statistically different and goes in opposite directions. While inventors in regulatory leader countries react by increasing their innovation efforts, which is in line with previous results found in the literature, inventors in follower countries react by decreasing their innovation efforts – a completely new result to the literature.

Table 1 — Main estimation results

Model	(1)	(2)
$CHANGE_{it}$	-0.0821** (0.0334)	-0.1118*** (0.0362)
$LEADER_{it}$	-0.1181** (0.0550)	-0.0986 (0.0606)
$CHANGE_{it}$ * $LEADER_{it}$	0.2173*** (0.0698)	0.2010** (0.0789)
Regulation level fixed effects	yes	yes
Country fixed effects	yes	yes
Year fixed effects	yes	yes
Observations	2825	2618
Countries	190	189

Note: *=significant at the 10% level, **=significant at the 5% level, ***=significant at the 1% level. The dependent variable is the log of the share of patents filed in automotive pollution control technologies by inventors from country *i* in year *t*. The models are estimated using OLS and include a full set of country, regulatory level and year dummies (not reported for brevity). Standard errors clustered at country level in parentheses.

6.2 Robustness tests

Results from a number of robustness tests are reported in table 2. In column 1, we use the share of pollution control technologies in all patent applications in the automobile sector (rather than in all sectors) as an alternative dependent variable. Unsurprisingly, the point estimates change in magnitude but our main result remains unaffected. The impact of a change in regulatory stringency is of opposite signs and of similar magnitudes for leader and follower countries. In column 2 we explore the sensitivity of our result to the way we define regulatory changes. We now define $CHANGE_{it}$ to be equal to one during 3 years starting the year of an increase in regulatory stringency. Our results remain qualitatively unaffected, although the standard errors tend to increase slightly, suggesting most of the impact happens during the year of the regulatory change and the following year. In column 3 we similarly try an alternative definition of regulatory leadership. We define $LEADER_{it}$ empirically, by selecting the countries that are ahead of the others. Our main result is unaffected.

In column 4 we check the robustness of our results to excluding small unrepresentative countries from the sample. We restrict the sample to countries having developed more than 500 inventions over our sample period, thereby dividing the sample size by almost three. Again, our main result is unchanged, and we are reassured that the results are not driven by countries that are very small contributors to innovation globally. Finally in column 5 we check that our results are not driven by the difference between null and positive values of the dependent variable. We drop all zeros from the dependent variable, directly taking the logs and reestimate our main model. The results are fully robust to this change. Interestingly, the coefficient on the interaction variable is now about three times larger in magnitude than the coefficient on the $CHANGE_{it}$ variable, suggesting that the positive impact of regulatory change on innovation in leader countries might be larger in absolute magnitude than the negative impact of the same change on follower countries, a result confirmed by a statistical test (p=0.0859).

Table 2 — Robustness checks

Model	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
$CHANGE_{it}$	-0.3037***	-0.0617**	-0.0683**	-0.0474**	-0.1638**
	(0.1073)	(0.0317)	(0.0374)	(0.0191)	(0.0791)
$LEADER_{it}$	-0.3606**	-0.0805	-0.0292	-0.1023*	-0.2946**
	(0.1471)	(0.0691)	(0.0422)	(0.0539)	(0.1284)
$CHANGE_{it}$ * $LEADER_{it}$	0.6175***	0.1330*	0.0865*	0.1421**	0.4506***
	(0.1965)	(0.0803)	(0.0440)	(0.0601)	(0.1654)
Regulation level fixed effects	yes	yes	yes	yes	yes
Country fixed effects	yes	yes	yes	yes	yes
Year fixed effects	yes	yes	yes	yes	yes
Observations	1528	2825	2825	1325	882
Countries	145	190	190	74	103

Note: *=significant at the 10% level, **=significant at the 5% level, ***=significant at the 1% level. The dependent variable is the log of the share of patents filed in automotive pollution control technologies by inventors from country *i* in year *t*. The models are estimated using OLS and include a full set of country, regulatory level and year dummies (not reported for brevity). Standard errors clustered at country level in parentheses.

7 Conclusion

In this paper we combine data on automobile emission standards and on patenting of associated compliance technologies in order to study the relationship between environmental regulation and innovation activity. Our dataset spans from 1992 to 2009. During this period, five different waves of standards have been adopted and around 140,000 pollution control innovations were patented worldwide. We exploit the fact that standards evolve differentially over time across countries in our dataset and that firms are differentially exposed to these standard changes because of the historical influence of domestic standards on companies in the car industry.

Consistent with our theoretical model our key result is that the reaction of inventors to a change in the level of regulation differs strongly across regulatory "leaders", who are the first to adopt a more stringent regulation globally, and regulatory "followers", who adopt later. While inventors in regulatory leader countries react to a tightening of emissions standards by increasing their innovation efforts, inventors in follower countries react by decreasing their innovation efforts. This result is novel to the literature, which has until now assumed an unambiguously positive relationship between regulatory tightening and innovation efforts.

Our findings have a number of wider implications. A first one is that they suggest that the relationship between environmental regulation and innovation activities needs to be understood as an inherently relational process between countries. Attention therefore needs to be paid to relative regulatory stringency between countries, rather than to absolute regulatory stringency. From a policy perspective, the results of the study suggest that the development of new clean technologies from the major innovating economies can be accelerated by domestic regulatory tightening, but only in countries which are frontrunners in terms of regulatory stringency. Countries that lag behind the former in terms of regulatory stringency are likely to see a decrease in innovation efforts following the tightening of domestic regulations. However, these lagging countries – which would generally include developing countries whose regulatory standards are invariably lower than those of developed economies – are likely to see an increase in the flow of technologies coming from inventors located in regulatory leader countries, as demonstrated by Dechezleprêtre et al. (2014).

Our analysis could be extended in several directions. First, we have not analysed the impact of foreign markets on domestic innovation, as is done by Dechezleprêtre and Glachant (2014). Secondly, we have not taken into account the impact of cross-border knowledge spillovers on innovation activities. An important limitation of our analysis is that our results apply to environmental product standards in the automobile sector, such that an important task for future research is to examine whether our findings apply to other sectors and apply to process-based regulations.

8 Bibliography

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