Research Policy 44 (2015) 244–257

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Environmental regulation and the cross-border diffusion of new technology: Evidence from automobile patents

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ARTICLE INFO

Article history:
Received 15 March 2013
Received in revised form 9 July 2014
Accepted 29 July 2014
Available online 4 September 2014

JEL classification:
O33, Q53, Q55

Keywords:
Pollution control technologies
Environmental regulation
Patents
International technology diffusion

ABSTRACT

We examine the impact of environmental regulation on the international diffusion of new technology through the patent system. We employ a dataset of automobile emission standards between 1992 and 2007 and corresponding data on cross-border patent inflows of technologies developed to comply with these standards. Our analysis, based on a research design of country pair years, shows it is "regulatory distance" between countries rather than absolute regulatory stringency per se that matters for cross-border patent inflows: the flow of compliance technologies rises when regulatory standards in the inventor and the recipient countries become "closer".

1. Introduction

There is widespread agreement that the enhanced cross-border diffusion of environmentally sound technologies (ESTs)[1] is key to addressing environmental problems (WCED, 1987; Popp, 2011; Beyer and Urpelainen, 2013). These flows of technology are particularly significant for developing countries because they are rapidly adding new capacity and, moreover, the vast majority of ESTs are still developed in OECD countries (Dechezleprêtre et al., 2011).

The question of how to accelerate cross-border flows of ESTs has stimulated a debate about the role of government policy. Much of the existing controversy in this area has surrounded intellectual property rights (IPRs) and the degree to which strengthening IPR regimes helps or hinders the international diffusion of new technology (see, for example, Hall and Helmers, 2010; Ockwell et al., 2011). By contrast, the impact of public environmental regulation on cross-border flows of new ESTs has proved less controversial, typically underpinned by a general assumption that tighter domestic environmental regulation automatically increases the cross-border flows of ESTs (Tébar Less and McMillan, 2005; Gallagher, 2006). Indeed, a number of past studies support this assumption, showing a positive relationship between domestic regulatory stringency and inflows of compliance technologies (Lanjouw and Mody, 1996; Popp et al., 2011; Dekker et al., 2012).

However, not all works show that more stringent domestic environmental regulation stimulates the international diffusion of ESTs. For example, Popp (2006) finds that tighter air pollution standards in the power sector in the US did not result in higher levels of compliance technology inflows from Germany and Japan, but only greater local innovative efforts. In addition, empirical studies into the relationship between regulation and cross-border technology flows suffer from various shortcomings. First, they do not use measures which directly capture actual regulatory stringency, with the majority instead relying on proxies such as pollution abatement expenditure (e.g. Lanjouw and Mody, 1996) or ratification of international environmental agreements (e.g. Dekker et al., 2012). Second, existing studies are mainly based on fairly small samples, particularly in terms of the number of recipient countries (e.g. Popp et al., 2011). Third, existing work has almost exclusively focused on environmental process standards, thereby neglecting the potentially crucial role of environmental product standards in the cross-border flow of ESTs.

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[1] ESTs are defined by Agenda 21 as technologies which 'protect the environment, are less polluting, use all resources in a more sustainable manner, recycle more of their wastes and products, and handle residual wastes in a more acceptable manner than the technologies for which they were substitutes.'

http://dx.doi.org/10.1016/j.respol.2014.07.017
0048-7333/

In this paper, we provide new evidence on the role that environmental regulation plays in cross-border flows of compliance-related technologies based on a newly constructed panel data set that combines the level of motor vehicle emissions product standards in 72 countries between 1992 and 2007 with patent filings in corresponding automotive emissions reduction technologies. National emission standards are all expressed in terms of European Union (EU) standards equivalent, making it possible to compare the regulatory level both across countries and across time. We complement these regulatory data with data on non-resident patents protecting technologies that are developed specifically to comply with automotive emissions standards. Data on inventors' country of residence for these patents allow us to measure cross-border technology flows, following an established tradition in the literature (Chan, 2010; Dechezleprêtre et al., 2013; Dekker et al., 2012; Eaton and Kortum, 1999; Lanjouw and Mody, 1996; Perkins and Neumayer, 2011; Popp et al., 2011; Yang and Kuo, 2007). To mitigate the well-known problem that many patent applications relate to technologies of low value, our outcome measure focuses on those patents that, after scrutiny, were actually *granted* by the foreign patent office, as opposed to the more expansive category of all patent *applications*[2]. During our sample period, 183,000 patents in automobile emissions control technologies were granted worldwide to non-residents.

Our main argument and findings can be summarized as follows: what matters for inflows of ESTs is not domestic regulatory stringency as such, but the level of regulation *relative* to potential source[3] countries, or what we call regulatory distance. Indeed, we find strong and robust evidence that countries receive more non-resident patents from source countries whose level of regulation is closer to their own. An increase in regulatory stringency simultaneously raises patent inflows from countries that have a higher regulatory level and decrease patent inflows from countries with lower regulation levels. Once we control for regulatory distance, absolute regulatory stringency in potential destination countries of technology inflows ceases to matter. Therefore the impact of absolute regulatory stringency on the total number of patent inflows is a priori ambiguous and depends on the country's regulatory position relative to that of major inventor countries.

Our paper relates to two strands of existing literature. First, our study draws from, and contributes to, work on the international diffusion of technology (Saggi, 2002; Keller, 2004). This literature has identified three channels through which new technology flows and where patent protection is frequently used: trade in goods, foreign direct investment and licensing (Smith, 2001; Eaton and Kortum, 2002; Branstetter et al., 2006). Work in this area has also sought to explore the domestic conditions which facilitate and impede the (successful) diffusion of new embodied and disembodied technological knowledge.

Second, our paper relates to the literature investigating the links between environmental policy and the cross-border diffusion of ESTs. Empirical work on this topic has mainly relied on survey data (Veugelers, 2012), CDM projects data (Dechezleprêtre et al., 2008; Schmid, 2012) and patent data (Dekker et al., 2012; Haščič et al., 2010; Haščič and Johnstone, 2011a; Popp et al., 2011; Verdolini and Galeotti, 2011). None of these papers analyses the impact of relative regulatory stringency (regulatory distance) on technology diffusion.

The paper is structured as follows. Section 2 develops our arguments regarding the relationship between environmental regulation and the international diffusion of technology. Section 3 explains why the automobile sector constitutes a good test-case for our hypotheses. Data are presented in Section 4 and the research design described in Section 5. Section 6 presents the results and robustness tests. A final section concludes.

2. Environmental regulation, innovation and international technology diffusion

The past two decades have witnessed a surge in inventive activity aimed at reducing the environmental impact of production and consumption activities (OECD, 2011; Bettencourt et al., 2013). A leading driver for the innovation of ESTs has been environmental regulations governing processes and/or products (Costantini and Mazzanti, 2012). A number of studies find compelling evidence that various measures of regulatory stringency are positively correlated with innovative inputs as measured by R&D expenditures (Jaffe and Palmer, 1997; Lanoie et al., 2011) and innovative outputs as measured by patents (Brunnermeier and Cohen, 2003; Johnstone et al., 2010; Lee et al., 2011).

The literature identifies several actors ("inventors") involved in the innovation of ESTs. One is producers whose processes or products are the subject of environmental regulation (Bergquist et al., 2013). A second set of actors are suppliers who sell ESTs in embodied or disembodied form to other firms (Perkins, 2007; Taylor et al., 2003; Horbach, 2008)[4]. Some of these firms specialise in ESTs, while others supply environmental technologies as part of a wider range of equipment, including ESTs integrated into process designs. A third set of actors are publicly-funded research facilities and universities which are known to play an especially important part in the development of more radical technologies.

While environmental regulation may drive the innovation of new ESTs, as well as provide an economic incentive for regulated parties to adopt these technologies, the question addressed in the present paper is whether it also plays a role in EST diffusion across borders. The answer is likely to depend, in part, on whether there exists pre-existing technologies abroad to supply regulation-induced demand. In the case of regulatory leaders (i.e. those who lead in the introduction of the most stringent policy), regulatory tightening may well be supplied by domestic innovation, not least because there is no sufficient supply of compliance technologies abroad. While demand-side incentives in one country may of course stimulate innovation in other countries and thus increase the supply of foreign ESTs potentially available to domestic adopters (de la Tour et al., 2011; Peters et al., 2012), evidence suggests that the impact of domestic policies on innovation is much stronger than that of foreign policies (Dechezleprêtre and Glachant, 2014). Available case-study evidence therefore shows that the adoption of stringent regulation in regulatory leader countries has stimulated predominantly domestic innovation of ESTs in various sectors (Beise and Rennings, 2005; Brandt and Svendsen, 2006; Popp, 2006).

However, once a particular compliance technology has been domestically developed to comply with a specific domestic standard, the adoption of similar environmental standards elsewhere may lead inventors to transfer their technology to these jurisdictions (Beise and Rennings, 2005; Huber, 2008). Inventors in early-regulating ("frontrunner") source countries are likely to possess a competitive advantage vis-à-vis potential domestic competitors in later-regulating ("follower") countries, stemming from the fact that their pre-existing compliance technologies benefit from dynamic scale economies and learning effects (Porter and van der Linde, 1995; Brandt and Svendsen, 2006). This provides an

[2] Our results are robust to using all filed patent applications, however.

[3] Note, we use the terms source and inventor country interchangeably.

[4] Note, the distinction between these first two categories may sometimes be blurred, in that some regulated firms may sell their inventions to others firms (e.g. through licencing).

incentive for inventors in source countries to market, sell and seek protection for their technologies in recipient countries which adopt similar standards to their own in response to growing demand[5].

Importantly, differences between regulatory followers and frontrunners would suggest that the transfer of newly-innovated technologies by patent holders will not be a simple positive function of regulatory stringency in the recipient country, with stricter regulations necessarily leading to more filing of EST patents from inventing countries. Instead, such filings should be greater where recipient country *j* adopts environmental standards similar to those in source country *i*, the economy in which the technology was originally designed to achieve compliance. That is, we expect flows of new ESTs through the patent system to be a function of regulatory "distance" between sending and receiving countries, i.e. the gap between regulatory standards in *i* and *j*. A similar point is made by Haščič and Johnstone (2009) who invoke the idea of a "ladder" of increasingly costly ESTs capable of complying with more stringent environmental policies. According to the authors, individual countries' position on this ladder is determined by their domestic regulation, with technologies consistent with domestic firms' profit maximisation transferred from countries 'situated on the same rung of the ladder'.

Based on this logic, it would follow that the implications of domestic regulatory changes will depend on whether the level of regulation in the (potential) recipient country is higher or lower than the one in the (potential) source country. Specifically, where domestic environmental regulatory stringency in country *j* is lower than in country *i*, we expect regulatory tightening in the former closer to levels found in the latter to increase foreign patent filings. The underlying logic is that the adoption of more stringent standards will necessitate the uptake of compliance technologies in country *j* which can readily be supplied by firms in country *i* owing to their previous domestic experience of innovating to comply with these standards (Beise and Rennings, 2005). Conversely, where standards in the (potential) recipient country *j* are already higher than the ones in the (potential) source country *i*, i.e. on a higher rung of Haščič and Johnstone's (2009) regulatory ladder, a further regulatory tightening of standards in country *j* should lead to fewer transfers from *i* to *j*. Simply put, firms in country *i* are less likely to have innovated compliance technologies required to comply with standards which are more stringent than those required domestically, and will therefore be even less able to supply foreign demand in country *j*, as the regulatory distance between countries *i* and *j* increases further. We therefore predict that:

The flow of newly-innovated ESTs from source country i to recipient country j increases as the regulatory distance between the two countries becomes smaller.

3. 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,

[5] Indeed, the rising value of their proprietary technology implies that foreign firms will want to protect their technology from imitation, particularly if there are other potential competitors in the recipient market.

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 (Pavlínekt, 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; Pavlínekt, 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[6] (Bailey et al., 2010; 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).

[6] A case in point would be the alliance between Renault (France) and Nissan (Japan) which involves the joint development of various technologies and the sharing of engines across different firms' models.

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 more likely to be transferred to 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

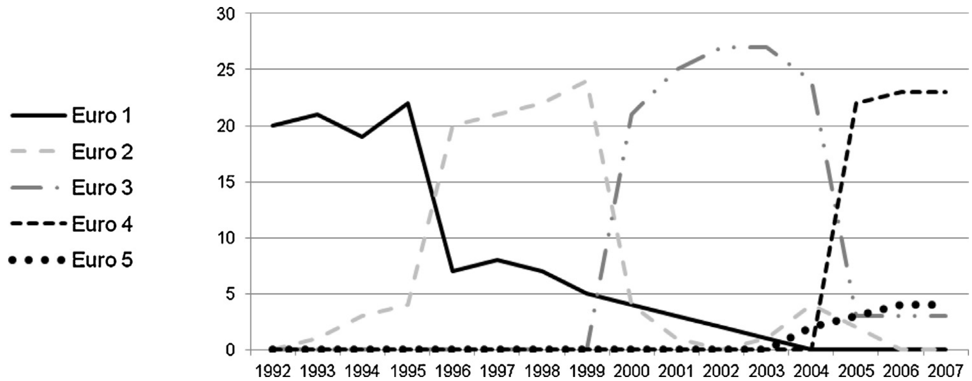

Fig. 1. Number of adopters of Euro equivalent standards in OECD countries 1992 2007

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 distance between countries. 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 the flow of ESTs through the patent system (Haščič et al., 2009; Perkins, 2007; Gallagher, 2006; Lee and Berente, 2013). A third salient characteristic is that non-resident patenting is a key feature of the automobile sector. This reflects the widespread flow of technologies among final producers and suppliers between different parts of their regional and/or global networks, as well as the licencing of technologies to foreign firms (Kumaraswamy et al., 2012). The incidence of non-resident patenting also reflects the importance of producers protecting their intellectual property from competitors. This includes patenting of technology in markets where the final product is sold.

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 1992–2007[7]. 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 NO_x) 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 Figs. 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.

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, 2010). 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 diagnostics systems; and oxygen, NO_x 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.

[7] 1992 is the first year for which we have data on environmental regulatory stringency, while 2007 is the last reliable year in the September 2010 version of the PATSTAT database.

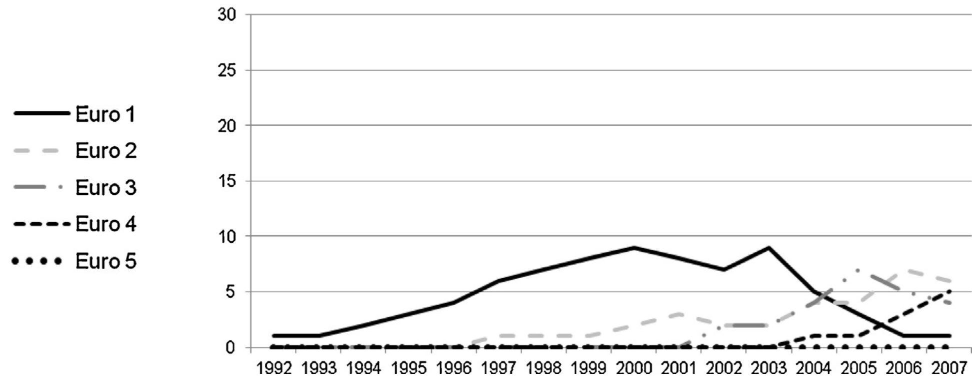

Fig. 2. Number of adopters of Euro equivalent standards in non OECD countries 1992 2007.

In our baseline estimation, we pool all technologies together, but in the sensitivity tests we analyse the main ones individually.

Information about the patent office that receives the patent was used to identify countries to which a particular invention flows. For patents filed at the European Patent Office (EPO) we use the list of EPO member states designated in the patent application. Applicants filing a patent at the EPO must designate the European countries to which they intend to transfer the patent once granted by the EPO. A European patent thus comes into existence effectively as a group of national patents in each of the designated countries (OECD, 2009)[8].

Our main outcome measure focuses on patents that were eventually granted by the foreign patent office. Our estimation sample comprises 183,101 patents granted in 45 destination countries (listed in Appendix 2). Although we restrict our main focus on granted patents, patents are counted by the year of their application, as the date of grant is mostly determined by administrative idiosyncrasies of the various patent offices. In addition, we check the robustness of our results to using all patent applications filed. We do so for two reasons: First, some patent offices do not provide information on whether patent applications were eventually granted. Hence, by additionally analyzing patent applications we take a larger sample of destination countries into account (namely 54 destination countries for patents filed instead of 45 destination countries for granted patents). Second, we wish to verify the consistency of our results with those of previous work which has relied on applications rather than grants to measure cross-border technology flows (Dekker et al., 2012)[9]. To identify the country where the technology was originally developed, we use information on the inventor's country of residence[10]. The resulting list of sources of relevant inventions comprises 108 countries.

A patent is an exclusive property right granted by a state to an inventor for a limited period of time. Since a patent is only valid in jurisdictions where it is granted, inventors must file a patent with the competent authority in each of the countries where they wish to protect their technology, a process known as non-resident patent filing (NRPF) when these countries differ from the one of the inventor. NRPF has been widely used in recent years as a measure of the flows of new technology from source to recipient countries (Dekker et al., 2012; Lanjouw and Mody, 1996; Perkins and Neumayer, 2011; Eaton and Kortum, 1999; Popp, 2006; Dechezleprêtre et al., 2013; Chan, 2010; Yang and Kuo, 2007)[11]. We follow a similar approach in the present paper, using the number of patents invented in country *i* and successfully patented in country *j* as an indicator of the number of inventions from country *i* which flow to country *j*.

There are several advantages of using patents to measure technology diffusion. 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)[12].

Using non-resident patents as an indicator of technology flows is nevertheless not without limitations. To start with, not all inventions are patented. The value of individual patents is also heterogeneous. However, this is less of an issue in the present paper to the extent that we focus not only on granted patents but on "exported" inventions, which are typically more valuable (Harhoff et al., 2003). 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 €5000 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)[13].

8 Once granted, the patent is automatically valid in each designated country, provided that the inventor pays designation fees in each of these countries. Note that since 1 April 2009 all European Patent Convention member states are automatically designated in EPO applications, such that this method would no longer be valid. In Section 6, we test that our results are robust to considering all European countries as a single entity and to the inclusion of dummy variables for EPO membership.

9 The fact that a patent application is not granted by the national patent office does not prevent the inventors from using it. The technology is unlikely to be licensed, however, meaning that technology diffusion might be less widespread.

10 Patents with multiple inventors are counted fractionally. For example, if two inventor countries are involved in an invention, then each country is counted as one half. If one of the multiple countries is the destination country, then the patent is not counted as a flow to the destination country. However it is counted as a fractional flow to the countries other than the inventor countries. Note that patents with multiple countries of invention only represent less than 5 per cent of the patents in our dataset.

11 Another popular approach to examining the diffusion of technology is through the use of patent citations data (e.g. Verdolini and Galeotti, 2011), although this is better suited to identifying cross-border knowledge spillovers than cross-border technology flows via market transactions.

12 Cohen et al. (2000) conducted a survey questionnaire administered to 1478 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.

13 75 per cent of inventions are patented in only one country.

5. Estimation framework

5.1. Baseline model specification: The effect of regulatory stringency

The number of technologies which flow across borders through the patent system is measured by P_{ijt}, the number of patents filed in country *j* by inventors from country *i* in year *t and subsequently granted*. We begin with a baseline model in which, consistent with conventional wisdom, it is assumed that absolute regulatory stringency in the recipient country determines inflows of patented ESTs from inventor countries. Our baseline model specification is thus as follows:

$$P_{ijt} = \alpha_1 REG_{jt-1} + \alpha_2 REG_{it-1} + \beta \mathbf{X}_{ijt} + \varepsilon_{ijt} \quad (1)$$

where REG_{jt-1} measures the stringency of regulation in country *j*, REG_{jt-1} controls for the stringency of regulation in source country *i*, $\mathbf{X}_{ijt}$ is a vector containing the set of other control variables, including a full set of country pair and year fixed effects, and ε_{ijt} is the error term. The regulatory variables are lagged by one year since it takes time for foreign inventors to react to changes in regulatory standards.

5.2. An alternative model specification: The effect of regulatory distance

In order to examine the influence of relative stringency and test our hypothesis, we define $REGDIST_{ijt--1}$, which captures the difference between the stringency of regulation in countries *i* and *j*. Formally, $REGDIST_{ijt-1} = abs(REG_{jt-1}-REG_{it-1})$ where REG_{it-1} and REG_{jt-1} denote the level of regulation in countries *i* and *j*, respectively, in year $t-1$. The reason to use the absolute value of regulatory distance is that we expect the impact of distance to be negative when the distance is positive, and positive when the distance is negative, implying that the effects would cancel each other out if distance itself rather than the absolute value was included. A further benefit of using the absolute distance is that it allows us to also control for both REG_{jt-1} and REG_{it-1}, thereby ensuring that it is not simply changes in these variables that are driving the results. Our specification incorporating distance is:

$$P_{ijt} = \alpha_1 REG_{jt-1} + \alpha_2 REGDIST_{ijt-1} + \alpha_3 REG_{it-1} + \beta \mathbf{X}_{ijt} + \varepsilon_{ijt} \quad (2)$$

5.3. Control variables

We include five control variables. The first accounts for the number of relevant inventions within the field of automotive ESTs from the source country available for potential transfer. We measure this by $PAT_{i,t-1}$, comprising the number of automotive EST inventions patented by inventors from country *i* anywhere in the world in year $t-1$. Any invention patented in several countries is thus only counted once. We expect a positive effect of this variable on technology flows from country *i* to country *j* because, all else equal, an increase in the number of technologies available to be patented in foreign economies should lead to higher inflows of non-resident patents.

A second control variable captures the stock of relevant patents previously filed in the recipient country *j*, including those by domestic inventors from country *j*. The impact of this variable is theoretically ambiguous in that it could have a positive (complementary) or negative (substitutive) effect on inflows of patented technology from abroad. On the one hand, the stock of patents is a good proxy for local absorptive capabilities, which previous research has shown are critical for the diffusion of advanced technologies (see Saggi, 2002). On the other hand, a high existing stock of patents may signal to foreign patent holders that the local market is already well-served by competing technologies, such that the economic payoff from having one's own innovation patented in this country is small. Following Peri (2005), the patent stock is calculated using the perpetual inventory method:

$$KPAT_{j,t} = \left(1-\delta\right) KPAT,\, t_{j,t-1} + PAT_{j,t}$$

where PAT_{jt} is the number of patents filed in country *j* in year *t*. The rate of depreciation of R&D capital, δ, is set at 15% in our main estimations[14]. To avoid endogeneity, we temporally lag this stock variable by one year, thus including $KPAT_{jt-1}$ in the estimation model.

As a third control variable, we include the number of automotive pollution-control patents filed in country *j* by inventors from countries other than country *i* in the previous year, denoted by $PAT_{\text{-}i,t-1}$. These patents cover technologies that are likely to compete with patents transferred by inventors from country *i*. A higher number of competing technologies may discourage transfers. Yet they might conversely attract more patents as firms in country *i* emulate their foreign competitors (Perkins and Neumayer, 2011). Since inventors from country *i* are unable to observe patents simultaneously filed by inventors from other countries, we assume that they form expectations about the number of patents transferred from other countries in year *t* based on the number of patents transferred in $t-1$[15]. Using the lagged value $PAT_{\text{-}i,t-1}$ also avoids a potential endogeneity issue that might arise because $PAT_{\text{-}i,t}$ is also a function of the regulatory level and regulatory distance.

A fourth control variable is meant to capture the size of the automobile market in destination countries since larger markets should attract more cross-country patent flows. Unfortunately, the International Organization of Motor Vehicle Manufacturers (OICA) only provides data with widespread geographic coverage on car sales for 2005–2012, whereas our dataset covers 1992–2007. However, automobile and automobile-related imports by the destination country are highly correlated with car sales (correlation coefficient = 0.71 over 2005–2012) and import data are readily available. We therefore use data on total automobile and automobile-component imports sourced from UN (2013) as a proxy for the size of the relevant market in destination countries.

We additionally include a measure of the degree of patent protection afforded by the recipient country. Several studies have shown that stricter patent laws have led to higher patent activity, e.g. Hall and Ziedonis (2001), Hu and Jefferson (2009), Lerner (2009) and Perkins and Neumayer (2011). We use Park's (2008) index of patent rights, denoted by IPR_{jt}, which codes countries with values running from 0 (no protection at all) to 5 (highest protection)[16]. Lastly, we account for factors that are specific to each country and to each country-pair but do not vary across time, such as language, spatial distance, and differences between patent offices in the scope and definition of what can constitute a patent[17], by employing an estimator that conditions out the country-pair fixed effects. Year-specific fixed effects are used to control for changes over time that affect all countries equally, such as oil prices. Table 1 presents summary variable statistics and a bivariate correlation

[14] The results are robust to using 10 per cent and 20 per cent discount rates instead. We initialize patent stocks for the year 1950 by setting the initial value in this year to zero.

[15] Consistent with an adaptive expectations model, we also experimented with a distributed lag, but the data suggest that the best predictor of $PAT_{\text{-}i,t}$ is $PAT_{\text{-}i,t-1}$. Rational inventors should therefore use $PAT_{\text{-}i,t-1}$ to predict $PAT_{\text{-}i,t}$.

[16] The data are interpolated to fill in gaps from missing years, but results are robust to using either the anterior or posterior value in time to impute missing rights protection values in a country.

[17] For example, it is known that patents in Japan are "narrower" being based on fewer claims to innovation, such that the main technology may be covered by one patent in Germany and by two patents in Japan.

Table 1
Summary statistics and bivariate correlation matrix.

	Mean	Std. dev.	Min.	Max.
Patent flow$_{ijt}$	8.83	42.01	0	796.83
Reg. recipient (REG_{jt-1})	1.89	1.29	0	5
Reg. source (REG_{it-1})	1.77	1.30	0	5
Reg. distance ($REGDIST_{ijt-1}$)	0.90	0.95	0	5
Inventions source (PAT_{it-1})	1.75	1.80	0	6.59
Knowledge stock ($KPAT_{jt-1}$)	6.49	2.02	0	9.30
Other countries' transfers (PAT_{-it-1})	4.80	2.13	0	7.72
Patent protection (IPR_{jt})	4.03	0.64	1.54	4.88
Car imports$_{jt-1}$	14.93	3.01	0	19.06

	I	II	III	IV	V	VI	VII	VIII
I: Patent flow$_{ijt}$	1							
II: Reg. recipient (REG_{jt-1})	0.06	1						
III: Reg. source (REG_{it-1})	0.09	0.49	1					
IV: Reg. distance ($REGDIST_{ijt-1}$)	−0.11	−0.08	−0.16	1				
V: Inventions source (PAT_{it-1})	0.31	−0.05	0.28	−0.04	1			
VI: Knowledge stock ($KPAT_{jt-1}$)	0.13	0.62	0.16	−0.08	−0.16	1		
VII: Other countries' transfers (PAT_{-it-1})	0.12	0.52	0.07	−0.09	−0.19	0.92	1	
VIII: Patent protection (IPR_{jt})	0.10	0.60	0.22	−0.03	−0.10	0.74	0.64	1
IX: Car imports$_{jt-1}$	0.05	0.32	0.16	0.02	−0.04	0.38	0.31	0.30

Notes: N = 18,741. Car imports and all patent-based variables (except the dependent variable) are logged.

matrix. Importantly, both these bivariate correlations and variance inflation statistics did not suggest substantial multi-collinearity problems between the three regulation variables.

5.4. Estimation technique and sample

Given the dependent variable is strictly non-negative, we do not use ordinary least squares, but a conditional fixed effects negative binomial estimator in our main estimations. The conditioning out of country-pair fixed effects means that all country pairs in which over the entire period there is not a single patent flow are dropped from the estimation[18]. As there is no option to obtain robust clustered standard errors in Stata for this estimator, we perform cluster-bootstrapping instead, which is typically regarded as the next best alternative (Cameron and Trivedi, 2009).

In our main estimations, we pool all cross-country flows. However, we additionally examine whether our findings hold when restricting the sample to non-resident patents filed by developed (OECD) country residents in, separately, developed and developing (non-OECD) countries, respectively. In additional estimations we restrict the sample even further, namely to patent flows between residents of major car producing developed countries and developing countries. Using data on car production obtained from the International Organization of Motor Vehicle Manufacturers (OICA), we define a major car manufacturer as among the top 25 locations for the production of cars at the end of our sample period (2006). The list of major car producing developed countries includes the following (in order of importance as locations for car production): Japan, USA, Germany, South Korea, France, Spain, Canada, Mexico, UK, Italy, Turkey, Belgium, Czech Republic, Poland, Sweden and Australia.

6. Results

6.1. Main results

Our main estimation results are presented in Table 2. Column 1 shows results for our baseline model specifications (Eq. (1)).

[18] This represents roughly 40% of potential observations. These can be regarded as irrelevant country pairs, that is, as country pairs that would never experience cross-country patent transfers from country i to country j under any condition.

Table 2
Main estimation results.

Model	(1)	(2)
Reg. recipient (REG_{jt-1})	0.0990***	0.0374
	(0.0301)	(0.0316)
Reg. distance ($REGDIST_{ijt-1}$)		−0.1429***
		(0.0209)
Reg. source (REG_{it-1})	−0.0729***	−0.0777***
	(0.0275)	(0.0264)
Inventions source (PAT_{it-1})	0.1043***	0.1097***
	(0.0185)	(0.0179)
Knowledge stock ($KPAT_{jt-1}$)	0.4279***	0.4228***
	(0.0476)	(0.0473)
Other countries' transfers (PAT_{-it-1})	0.2160***	0.2097***
	(0.0279)	(0.0284)
Patent protection (IPR_{jt})	0.2274***	0.2295***
	(0.0721)	(0.0720)
Car imports$_{jt-1}$	0.0154**	0.0159**
	(0.0075)	(0.0076)
Observations	18,741	18,741
Country-pairs	1276	1276

Note:
* = significant at the 10% level,
** = significant at the 5% level,
*** = significant at the 1% level. The dependent variable is the number of patent flows from country i to country j in year t and subsequently granted. The models are estimated using a conditional country-pair fixed-effects negative binomial estimator and include a full set of year dummies (not reported for brevity). Cluster-bootstrapped standard errors in parentheses.

Consistent with several previous studies, we find that a change in the domestic level of regulation in potential recipient country j exerts a statistically significant impact on patented technology inflows from foreign countries. That is, countries that increase the stringency of tailpipe emissions standards receive more inflows of automotive ESTs through the patent system from innovating countries.

Column 2 presents results for the alternative model specification given by Eq. (2). Rather than absolute regulatory stringency alone, this estimation model additionally includes absolute regulatory distance as an explanatory variable, thus allowing us to estimate the effect of regulatory distance controlling for the level of absolute stringency in both the recipient and the source countries. Consistent with our hypothesis, column 2 shows a statistically significantly negative relationship for our regulatory distance variable, indicating that the number of newly-innovated automotive

Table 3
Estimation results for developed–developing (and developed–developed) country flows.

Model	(1) Developed –Developing	(2) Developed –Developing	(3) Developed (major)–Developing	(4) Developed (major)–Developing	(5) Developed –Developed	(6) Developed –Developed
Reg. recipient (REG_{jt-1})	0.1131**	0.0095	0.1066	−0.0493	0.0837*	0.0727
	(0.0498)	(0.0543)	(0.0689)	(0.0917)	(0.0455)	(0.0461)
Reg. distance ($REGDIST_{ijt-1}$)		−0.1337**		−0.1946**		−0.1608***
		(0.0605)		(0.0937)		(0.0272)
Reg. source (REG_{it-1})	−0.0091	0.0981	−0.0352	0.1298	−0.1101***	−0.1196***
	(0.0867)	(0.1117)	(0.0912)	(0.1251)	(0.0242)	(0.0250)
Inventions source (PAT_{it-1})	−0.0255	−0.0257	−0.0138	−0.0177	0.1113***	0.1187***
	(0.0377)	(0.0379)	(0.0650)	(0.0667)	(0.0214)	(0.0203)
Knowledge stock ($KPAT_{jt-1}$)	0.2920***	0.2995***	0.2704***	0.2788***	0.4694***	0.4495***
	(0.0540)	(0.0551)	(0.0680)	(0.0682)	(0.0540)	(0.0541)
Other countries' transfers (PAT_{-it-1})	0.2158***	0.2077***	0.2295***	0.2190***	0.2282***	0.2222***
	(0.0479)	(0.0483)	(0.0422)	(0.0422)	(0.0326)	(0.0325)
Patent protection (IPR_{jt})	−0.1053	−0.1236	−0.1021	−0.1241	0.2865***	0.2991***
	(0.2046)	(0.2106)	(0.3155)	(0.3179)	(0.0862)	(0.0846)
Car imports$_{jt-1}$	0.3472***	0.3456***	0.3596***	0.3588***	0.0118	0.0131*
	(0.0713)	(0.0716)	(0.0612)	(0.0619)	(0.0073)	(0.0072)
Observations	3042	3042	1935	1935	10,095	10,095
Country-pairs	213	213	135	135	683	683

Note:
* = significant at the 10% level,
** = significant at the 5% level,
*** = significant at the 1% level. The dependent variable is the number of patent flows from country *i* to country *j* in year *t* and subsequently granted. The models are estimated using a conditional country-pair fixed-effects negative binomial estimator and include a full set of year dummies (not reported for brevity). Cluster-bootstrapped standard errors in parentheses.

ESTs which flow between countries increases when the difference between the two countries' regulatory levels decreases. At the sample mean, a decrease of regulatory distance between countries of one level on the Euro-equivalent scale (e.g. if the source country is at Euro 2 and the recipient moves from Euro 1 to 2) is estimated to increase the number of non-resident patents filed in the recipient country (and subsequently granted) by 14.3%[19]. Importantly, once we account for regulatory distance between source and recipient countries, the coefficient of the absolute regulatory stringency in recipient countries becomes virtually zero and statistically insignificant. Thus, in accordance with our hypothesis, it is regulatory distance that matters rather than absolute regulatory stringency in recipient countries.

Turning to controls, an increase in the regulatory stringency in the source country appears to decrease patent outflows from this country. One possible explanation is that the innovation of ESTs which are capable of complying with higher domestic standards is more difficult, costly and time-consuming. Accordingly, regulatory tightening induces a shift of resources towards a smaller number of higher-quality innovations, with the result that there are fewer (recently invented) inventions to transfer through the patent system. Another complementary explanation is that, as domestic inventors turn their attention towards inventing technologies designed to comply with more stringent domestic standards, a smaller share of their inventive effort is suitable for other countries with lower levels of regulatory stringency. We intend to explore these hypotheses in future work which will examine the relationship between invention, cross-border technology flows and environmental regulation. Our variables capturing the number of patented automotive ESTs available to transfer, the number of relevant patents filed in the destination country by inventors from other countries and total imports of automobiles and automobile-related components (our proxy for the size of the domestic market) and the strength of intellectual property rights (IPRs) all turn out statistically significant with the anticipated positive sign. The pre-existing stock of relevant patents filed in the destination country also has a statistically significant positive effect, suggesting they function as complements rather than substitutes for new technology inflows.

How substantively strong is the effect of regulatory distance compared to the impact of other statistically significant variables? Judged by a one standard deviation increase in respective variable values, regulatory distance has an effect that is almost three times stronger than the effect of total car imports, our proxy for domestic market size. It is similar in substantive effect size to the impact of domestic patent protection and only a little smaller than the effect size stemming from a higher number of available inventions in source countries. Only the domestic knowledge stock and other countries' transfers in the previous year have a stronger substantive effect, namely five times and three times stronger, respectively.

6.2. The specificity of developed-developing country flows

Much of the debate on cross-border technology flows and transfers has focused on the movement of ESTs from developed to developing countries (Ockwell et al., 2011; Gallagher, 2006; IPCC, 2007). As shown in Table 3, restricting the sample to non-resident patents filed by developed (OECD) country residents in developing (non-OECD) countries in columns 1 and 2 and additionally to non-resident patents filed by residents from major car producing developed countries in columns 3 and 4, we find similar results for our central explanatory variable compared to the main estimations. As before, regulatory distance between countries *i* and *j* exerts a statistically significant effect. With distance included, absolute regulatory stringency in recipient countries has no statistically significantly positive impact on inflows of patented ESTs (columns 2 and 4), suggesting again that it is regulatory distance that matters rather than absolute regulatory levels in recipient developing countries. Even on its own, absolute regulatory stringency in recipient countries is marginally statistically insignificant in column 3 and absolute regulatory stringency in source countries (rather than regulatory distance) does not matter for flows between developed and developing countries. The results for control variables are similar with two exceptions: neither the supply of foreign

[19] In Poisson and negative binomial models, coefficients can be interpreted as semi-elasticities.

Table 4
Robustness tests (I).

Model	(1)	(2)	(3)	(4)	(5)
Reg. recipient (REG_{jt-1})	0.0382	0.0122	0.0262	0.0384	0.0047
	(0.0326)	(0.0285)	(0.0279)	(0.0318)	(0.0181)
Reg. distance ($REGDIST_{ijt-1}$)	−0.1479***	−0.1342***	−0.1149***	−0.0662**	−0.0977***
	(0.0470)	(0.0252)	(0.0190)	(0.0294)	(0.0134)
Reg. distance squared ($(REGDIST_{ijt-1})\hat{2}$)	0.0024				
	(0.0229)				
Reg. source (REG_{it-1})	−0.0778***	−0.0724***	−0.1037***	0.1981***	−0.0219
	(0.0262)	(0.0247)	(0.0236)	(0.0357)	(0.0162)
Inventions source (PAT_{it-1})	0.1098***	0.1167***	0.0245	0.1034***	0.1738***
	(0.0178)	(0.0180)	(0.0186)	(0.0179)	(0.0208)
Inventions destination (PAT_{it-1})		−0.0633***			
		(0.0157)			
Knowledge stock ($KPAT_{jt-1}$)	0.4225***	0.4830***	0.3906***	0.4270***	0.3181***
	(0.0479)	(0.0423)	(0.0447)	(0.0480)	(0.0544)
Other countries' transfers (PAT_{-it-1})	0.2098***	0.1932***	0.0570*	0.2180***	0.3550***
	(0.0285)	(0.0309)	(0.0335)	(0.0276)	(0.0332)
All other transfers			0.2604***		
			(0.0192)		
Patent protection (IPR_{jt})	0.2289***	0.2030**	0.2053***	0.2368***	0.0930
	(0.0727)	(0.0820)	(0.0665)	(0.0696)	(0.0630)
Car imports$_{jt-1}$	0.0159**	0.0180***	0.0178***	0.0145**	0.0153**
	(0.0075)	(0.0066)	(0.0069)	(0.0073)	(0.0066)
Observations	18,741	18,294	18,741	18,741	28,287
Country-pairs	1276	1241	1276	1276	1935

Note:
* = significant at the 10% level,
** = significant at the 5% level,
*** = significant at the 1% level. The dependent variable is the number of patent flows from country *i* to country *j* in year *t* and subsequently granted except in column 5, where the dependent variable is the number of patent application flows from country *i* to country *j* in year *t*. All models are estimated using a conditional country-pair fixed effects negative binomial estimator with cluster-bootstrapped standard errors in parentheses. All models include a full set of year dummies (not reported for brevity).

inventions nor the level of patent protection in the recipient developing country matter for flows from developed to developing countries. Columns 5 and 6 report results for cross-border patent flows between developed country pairs. We find that the results are very similar to the main estimation results.

6.3. Robustness tests

Results from a number of robustness tests are reported in Tables 4 and 5. In the interest of space, we only report estimates for Eq. (2), which includes our main explanatory variable. In column 1 of Table 4, we explore whether the effect of regulatory distance on granted patent inflows is non-linear. We include the square term of regulatory distance to test for such non-linearity, but find no evidence for it. The implicit assumption of a linear effect in our main estimations is thus well supported.

In column 2 we include an additional explanatory variable that controls for the lagged number of inventions in the destination country, $PAT_{j,t-1}$, by domestic inventors. The impact of this variable is theoretically ambiguous. Strong domestic innovative effort could act as a complement to the cross-border flow of patents or as a substitute. We find that a larger number of domestic inventions in the previous year exerts a negative impact, suggesting that domestic inventions and cross-border technology flows act as subsitutes rather than complements. Our main result is unaffected.

Our results could be spurious if our dependent variable were to simply capture general patent flows in all technologies (rather than EST flows specifically), which are driven by bilateral trade and FDI relationships. In column 3, we address this concern by adding the total flow of patents from country *i* to country *j* in year *t* in all technologies other than automotive emissions abatement technology as an additional control variable. The result for the variable measuring regulatory distance between source and recipient country is fully robust.

Our results could also be spurious if there is strong reverse causality, namely if a larger cross-country flow of patents induces receiving countries to change their regulatory standards, rather than the other way around. To address this potential endogeneity concern, following Kellenberg (2009) we use lagged regulatory stringency in near-by countries as an instrument for domestic regulatory stringency (column 4). We define regulatory stringency in near-by countries as the weighted average of regulatory stringency in other countries, where the weight is 1/(distance squared), thus assuming that the importance of more distant countries falls off very rapidly. Regulatory stringency in near-by countries is strongly related to domestic regulatory stringency (with a t-statistic in excess of 35) and thus a strong instrument. It should also be exogenous since regulatory stringency in neighbouring countries should not directly influence the flow of technologies received domestically other than through its effect on domestic stringency. Using this instrument and replacing actual regulatory standards in countries *i* and *j* with their predicted values from the "first-stage" instrumental variable regression, we find that the main result on regulatory distance holds but the point estimate decreases in absolute terms (by about 30%). This would suggest that there is indeed some mild endogeneity bias in the results reported above. However, the regulatory distance variable remains highly statistically significant, suggesting that any reverse causality is not so great as to invalidate our results. Note that there is one significant difference in results in moving to the instrumental variable regression, namely that the coefficient of the regulatory standard in the source country now turns positive (instead of negative), which is more in line with what one would expect.

In column 5, rather than all patents granted, we use flows of all patent applications to construct the dependent variable and the controls. As mentioned previously, some patent offices do not provide information to PATSTAT on patents eventually granted, so our sample size of destination countries increases from 45 to 54. Another advantage of additionally analyzing patent applications is that we can explore whether our findings hold when using a measure similar to the one used in at least one other important study (Dekker et al., 2012). The use of patent applications also provides

Table 5
Robustness tests (II).

Model	(1)	(2)	(3)	(4)	(5)	(6)
Reg. recipient (REG_{jt-1})	−0.0260	−0.0214	−0.0452	−0.0768	0.0676*	0.0473
	(0.0545)	(0.0320)	(0.0293)	(0.0506)	(0.0405)	(0.0288)
Reg. distance ($REGDIST_{ijt-1}$)	−0.1639***	−0.2699***	−0.0722***	−0.0996***	−0.0927***	−0.1294***
	(0.0461)	(0.0273)	(0.0214)	(0.0354)	(0.0295)	(0.0323)
Reg. source (REG_{it-1})	0.1105**	−0.0551	−0.0768***	−0.0993***	−0.2221***	−0.2250***
	(0.0520)	(0.0466)	(0.0276)	(0.0325)	(0.0324)	(0.0398)
Inventions (PAT_{it-1})	0.1538***	0.1893***	0.1451***	0.0366	0.2596***	0.0951***
	(0.0306)	(0.0198)	(0.0195)	(0.0407)	(0.0251)	(0.0218)
Knowledge stock ($KPAT_{jt-1}$)	0.0063	0.4070***	0.3193***	0.4147***	0.3663***	0.4302***
	(0.0474)	(0.0513)	(0.0445)	(0.0752)	(0.0531)	(0.0626)
Other countries' transfers (PAT_{-it-1})	0.2434***	0.1881***	0.1593***	0.2774***	0.2725***	0.1502***
	(0.0388)	(0.0321)	(0.0225)	(0.0434)	(0.0434)	(0.0392)
Patent protection (IPR_{jt})	0.6050***	0.2608***	0.0531	0.4997***	0.3377***	0.3397***
	(0.1776)	(0.0936)	(0.0702)	(0.1442)	(0.0930)	(0.1170)
Car imports$_{jt-1}$	−0.2250***	0.0154*	0.0269***	0.0255**	0.0082	0.0161*
	(0.0475)	(0.0088)	(0.0086)	(0.0106)	(0.0092)	(0.0083)
Recipient EPO member$_{jt}$			0.8536***			
			(0.1471)			
Source EPO member$_{it}$			0.1481			
			(0.1419)			
Source and recipient EPO member$_{ijt}$			0.6548***			
			(0.1487)			
Observations	6480	15,639	18,741	3105	10,527	11,730
Country-pairs	448	1066	1276	210	718	798

Note:
* = significant at the 10% level,
** = significant at the 5% level,
*** = significant at the 1% level. The dependent variable is the number of patent flows from country *i* to country *j* in year *t* and subsequently granted. In column 1, EU15 countries are considered as a single entity. Column 2 drops Germany, Japan and USA from the sample. Column 3 includes EPO member dummy variables. Column 4 restricts the sample to OECD major car producers, columns 5 and 6 to patents related to fuel injection technologies and on-board diagnostics systems, respectively. All models are estimated using a conditional country-pair fixed effects negative binomial estimator with cluster-bootstrapped standard errors in parentheses. All models include a full set of year dummies (not reported for brevity).

a less restrictive measure of technology flows, in that some non-granted applications may nevertheless be the result of R&D, the product of which may be new technology previously unavailable in the recipient country. Again, our results uphold and the substantive effect of regulatory distance on patent applications is very close to that for granted patents as the dependent variable, with the two point estimates statistically indistinguishable from each other.

Another major concern is that our results could be spuriously driven by the fact that EU states move together in terms of regulatory level. We address this issue in column 1 of Table 5 by merging European countries into one single entity. The results are remarkably robust to this modification. In column 2, we exclude Japan, Germany and the US – three of the main sources and destinations of patents – from the estimation sample. The results are fully consistent with the main estimations, suggesting they are not driven by the presence of major source and recipient countries. The substantive effect of regulatory distance practically doubles compared to the baseline estimation model.

Patents filed with the EPO rather than national patent offices pose a difficulty that we have tackled via the specific allocation mechanism explained in Section 4. To account for the fact that this may over-state the amount of patent flows from, to and between EPO countries, in column 3 we include dummy variables for EPO members (for destination country EPO members, source country EPO members and the interaction between the two, i.e. when both source and destination countries are EPO members). The coefficient size of our regulatory distance variable is smaller in this model compared to baseline, but it remains statistically significantly different from zero.

In column 4 we restrict the sample to dyads consisting only of developed (OECD) countries that are major car producers as both sources and recipients of flows. One may wonder whether the effect of relative regulatory distance becomes weakened in such dyads for which cross-border patent flows may be more determined by strategic gaming incentives of car producers. We find that the coefficient on regulatory distance is now smaller in magnitude compared to the baseline model, consistent with such reasoning.

In columns 5 and 6, we use alternative dependent variables, restricting the sample to fuel injection technologies in column 5 and on-board diagnostics (OBD) technologies in column 6. Each of these groups of technologies represent about one third of the dataset. Again, our results for recipient regulatory distance are robust to changes in the dependent variable.

7. Conclusion

In this paper we use data on automobile emission standards and non-resident patenting of associated compliance technologies in order to study the relationship between environmental product regulation and the cross-border flows of ESTs through the patent system. We find that rather than absolute levels of regulatory stringency per se, it is relative stringency (or what we call regulatory distance) between source and destination countries that matters for the cross-border flow of EST patents in the automobile sector. We thus find robust evidence that countries receive more emissions reduction technology patents where their regulatory standards become closer to those in inventor countries. In fact, once we control for regulatory distance, absolute regulatory stringency in potential destination countries of technology inflows ceases to matter. A possible explanation for the role of regulatory distance is that regulation-driven demand for ESTs is more likely to be supplied by foreign innovators where these countries have already innovated compliance technologies in response to similar standards.

We caution against inferring too much from our findings. They only apply to newly-innovated ESTs covered by patents and thus say nothing about the flows of older technologies not covered by patents. Nor do they say anything about the cross-border

diffusion of environmentally-relevant technology through knowledge spillovers (Verdolini and Galeotti, 2011). Moreover, 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 regarding regulatory distance apply to other sectors and apply to process-based regulations.

Nevertheless, our findings have a number of wider implications. One is that they suggest that the cross-border flow of newly-innovated ESTs through the patent system needs to be understood as an inherently relational process. Attention therefore needs to be paid to relative regulatory stringency between source and recipient countries. From a policy perspective, the results of the study suggest that the inflow of new ESTs from the major innovating economies can be accelerated by domestic regulatory tightening, but only in countries which lag behind the former in terms of regulatory stringency. These lagging countries would generally include developing countries whose regulatory standards are invariably lower than the key source countries of ESTs which are developed economies.

Appendix 1.

Definition of IPC codes (following Haščič et al., 2009 and Vollebergh, 2010)

Air-fuel ratios	
F01N3/05	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
F02M67	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
F02M23	Apparatus for adding secondary air to fuel-air mixture
F02M25	Engine-pertinent apparatus for adding non-fuel substances or small quantities of secondary fuel to combustion-air, main fuel, or fuel-air mixture
F02M3	Idling devices
Oxygen, NOX and temperature sensors	
F01N11	Monitoring or diagnostic devices for exhaust-gas treatment apparatus
F02D41/14	Electrical control of supply of combustible mixture or its constituents (introducing closed-loop corrections)
Fuel injection systems	
F02M39	Arrangements of fuel-injection apparatus with respect to engines; Pump drives adapted top such arrangements
F02M41	Fuel-injection apparatus with two or more injectors fed from a common pressure-source sequentially by means of a distributor
F02M43	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
F02M45	Fuel-injection apparatus characterized by having a cyclic delivery of specific time/pressure or time/quantity relationship
F02M47	Fuel-injection apparatus operated cyclically with fuel-injection valves actuated by fluid pressure
F02M49	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
F02M51	Fuel injection apparatus characterized by being operated electrically
F02M53	Fuel-injection apparatus characterized by having heating, cooling, or thermally- insulating means
F02M55	Fuel-injection apparatus characterized by their fuel conduits or their venting means
F02M57	Fuel injectors combined or associated with other devices
F02M59	Pumps specially adapted for fuel-injection and not provided for in groups F02M 39/00 to F02M 57/00
F02M61	Fuel injection not provided for in groups F02M 39/00 to F02M 57/00
F02M63	Other fuel-injection apparatus, parts, or accessories having pertinent characteristics not provided for
F02M69	Low-pressure fuel-injection apparatus
F02M71	Combinations of carburetors and low-pressure fuel-injection apparatus
Exhaust gas recirculation (EGR) valves	
F01N5	Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy
On-board diagnostics systems	
F02D41	Electrical control of combustion engines; Electrical control of supply of combustible mixture or its constituents
F02D43	Conjoint electrical control of two or more functions, e.g. ignition, fuel-air mixture, recirculation, supercharging, exhaust-gas treatment
F02D45	Electrical control not provided for in groups F02D 41/00 to F02D 43/00
F02M51	Fuel injection apparatus characterized by being operated electrically
F01N9	Electrical control of exhaust gas treating apparatus
Crankcase emissions and control	
F01M13/04	Crankcase ventilating or breathing: having means of purifying air before leaving crankcase, e.g. removing oil
Catalytic converters	
F01N3/08-34	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust; for rendering innocuous by thermal or catalytic conversion of noxious components of exhaust
B01D53/92-96	Separation of gases or vapors; Recovering vapors of volatile solvents from gases; Chemical or biological purification of engine exhaust gases; Regeneration, reactivation or recycling of reactants
B01J23/40-46	Catalysts comprising metals or metal oxides or hydroxides; of the platinum group metals

Appendix 2.

List of recipient countries in sample.

Algeria	Germany	Poland
Argentina	Greece	Portugal
Australia	Hong Kong	Romania
Austria	Hungary	Russia
Belgium	Iceland	South Korea
Bulgaria	Ireland	Singapore
Canada	Italy	Slovakia
Chile	Japan	Spain
China	Luxembourg	Sweden
Cyprus	Mexico	Switzerland
Czech Republic	Morocco	South Africa
Denmark	Netherlands	Turkey
Egypt	New Zealand	UK
Finland	Norway	USA
France	Philippines	Ukraine

Additional countries when considering patent applications instead of grants.

Brazil	Guatemala	Israel
Chile	India	Panama
Ecuador	Indonesia	Uruguay

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