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

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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 transfer of compliance technologies rises when regulatory standards in the inventor and the recipient countries become "closer". Consistent with this main result, we find that in aggregate destination countries only receive a larger total inflow of patents as a consequence of regulatory tightening if their previous regulatory standard is below that of the major innovating source countries.

Keywords: pollution control technologies, environmental regulation, patents, international technology diffusion

JEL classification: O33, Q53, Q55

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; Stern 2007; Popp 2011; Beyer and Urpelainen forthcoming). Technology transfer is 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 the cross-border transfer 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, ICTSD 2008; Hall and Helmers 2010; Ockwell et al. 2011). By contrast, the impact of public environmental regulation on cross-border transfers of new ESTs has proved less controversial, typically been underpinned by a general assumption that tighter domestic environmental regulation automatically increases the transfer 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

[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.'

higher levels of transfers from Germany and Japan, but only greater local innovative efforts. In addition, empirical studies into the relationship between regulation and technology transfer 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 stimulating the international transfer of ESTs.

In this paper, we provide new evidence on the role that environmental regulation plays in the international transfer 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 pollution-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 moves closer to their own. An increase in regulatory stringency simultaneously raises patent inflows from countries that have a higher regulatory level and decrease patent transfers from countries with lower regulation levels. Once we control for regulatory distance, absolute regulatory stringency in potential destination countries of technology inflows completely 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

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

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

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 2011; 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. The relationship between environmental regulation and international technology diffusion

Environmental regulation provides an economic incentive for regulated parties to acquire compliance technology. The question addressed in the present paper is whether this regulation-induced demand is likely to stimulate foreign owners of ESTs to transfer their technologies to the regulating home country. The answer is likely to depend, in part, on whether there exists pre-existing technologies abroad to supply this demand. In the case of regulatory frontrunners (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 EST potentially transferable (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 2012). In fact, in the passenger car sector which forms the focus of the present study, early-regulating countries such as Japan, Germany and US established an early lead in the innovation of pollution reduction and control technologies (Gerard and Lave 2005; Lee et al. 2011). Available case-study evidence shows that the adoption of stringent regulation in regulatory leader countries has also stimulated predominantly domestic innovation of ESTs in other 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 ("leader") 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, in turn, provides an incentive for inventors in source countries to transfer their technologies to recipient countries which adopt similar standards to their own in response to growing demand.[4]

Importantly, differences between regulatory followers and leaders 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 the transfer 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

[4] 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.

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:

H1. More newly-innovated ESTs will be transferred from source country i to recipient country j where the regulatory distance between the two countries becomes smaller.

Applied within a global context, this hypothesis would suggest that absolute regulatory tightening in countries which lag the major source countries of ESTs is likely to lead to higher absolute numbers of inward patent filings, as the regulatory distance between the respective countries shrinks. These laggards will include developing countries, whose standards are invariably below those found in the major innovators of ESTs, which are all high-regulating developed economies. Conversely, for similar reasons of regulatory distance, the domestic tightening of environmental standards in countries which are at or higher than the level of regulation in major source countries is likely to lead to a reduction in transfers through the patent system. This will inevitably mean frontrunner developed economies. In other words, the effect of domestic regulatory stringency on the *total* number of patents taken out by foreign owners/inventors of ESTs will depend on the relative regulatory position of countries, such that regulatory tightening will have different implications in regulatory leaders and followers. We explicitly test this logical extension from our first hypothesis in our empirical analysis and thus formulate as our second hypothesis:

H2. A recipient country that tightens its regulatory standards will receive a higher absolute number of newly-innovated ESTs if it is lagging in regulatory standards behind the major innovating countries. In contrast, regulatory tightening in a country that is at or above the standard in major innovating countries will not receive more newly-innovated ESTs.

3. The automobile sector

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 transfer of ESTs through the patent system (Haščič et al. 2009; Perkins 2007; Gallagher 2006). Third, 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). It is also an industry in which external suppliers play a significant role, not only in manufacturing, but also in technological innovation. A relatively small number of European, Japanese, US and South Korean multinational final producers dominate the industry worldwide. The past decade has also witnessed the rapid growth of Chinese manufacturers – many of them working with various foreign partners. These producers offer a variety of models and are in significant competition with each other for customers who can relatively easily switch between different brands. The production of passenger cars themselves is geographically concentrated in a number of macro-regions (largely Europe, North America and Asia) and, within these regions, a small number of countries account for a large share of output. A much larger number of countries, however, have some involvement in the automotive production chain.

One implication of the above is that the automobile industry is a competitive one which, in many segments of the market, is highly price-sensitive. This has consequences for technology, including environmental ones, in that achieving higher levels of emissions performance involves more costly compliance technologies (Perkins 2007). As a result, manufacturers typically engineer vehicles to comply with domestic emissions 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. Another corollary of the structure of the automobile industry is that technology transfer (and associated non-resident patenting) is a key feature as technologies are transferred between parts of multinational production networks and associated suppliers in different countries. These technologies include newly-innovated ESTs.

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.[5] 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.

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).

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

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[5] 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.

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.

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). 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, 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.

Information about the patent office that receives the patent was used to identify countries to which a particular invention has been transferred. 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 analysing 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 transfers (Dekker et al. 2012).[6] To identify the country where the technology was originally developed, we use information on the inventor's country of residence.[7] 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 transfer 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 et al. 2007; Dechezleprêtre et al. 2013; Chan 2010; Yang and Kuo 2007). [8] We follow a similar approach in the present paper,

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[6] 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.

[7] 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.

[8] 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 technology transfer via market transactions.

using the number of patents invented in country *i* and successfully patented in country *j* as an indicator of the number of inventions transferred from country *i* 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, trade or foreign direct investments cannot be easily disaggregated. Second, patents are recorded for all inventors, while R&D expenditures is not reported for small and medium sized firms and international trade is only reported above certain thresholds. 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).[9]

Using non-resident patents as an indicator of technology transfer 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 also 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 €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

[9] 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.

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).[10]

5. Estimation framework

5.1 Baseline model specification: the effect of regulatory stringency

The number of technologies transferred 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:

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

where REG_{jt-1} measures the stringency of regulation in country *j*, REG_{it-1} controls for the stringency of regulation in source country *i*, $\boldsymbol{X}_{ijt}$ 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 hypothesis H1, we define $REGDIST_{ijt-1}$, which captures the difference between the stringency of regulation

[10] 75 per cent of inventions are patented in only one country.

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:

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

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 transfers from country i to country j because, all else equal, more non-resident patents should come from countries that have a higher number of technologies available to be patented in foreign economies.

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 transfers 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:

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

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 per cent in our main estimations.[11] 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 $PAT_{-i,t-1}$. 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*

[11] 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.

based on the number of patents transferred in t-1.[12] Using the lagged value $PAT_{-i,t-1}$ also avoids a potential endogeneity issue that might arise because $PAT_{-i,t}$ is also a function of the regulatory level and regulatory distance.

We include two further variables to control for factors unrelated to the automobile industry, but affecting general technology transfer between countries. Firstly, a measure of the degree of patent protection afforded by the recipient country is included. 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).[13] Secondly, in order to capture changes to the general attractiveness of countries as locations to transfer and protect firms' technology, we use country j's per capita income ($GDPPC_{jt}$), with data taken from World Bank (2010). All else equal, richer countries should attract more non-resident filings, including environmental-related ones (Perkins and Neumayer 2011). Lastly, we control 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[14], by employing an estimator that conditions out the country-pair fixed effects. Year-specific fixed effects are used to

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

[13] 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.

[14] 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.

control for changes over time that affect all countries equally, such as oil prices. Table 1 presents summary variable statistics.

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 transfer are dropped from the estimation.[15] 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).

6. Results

6.1 Main results

Our main estimation results are presented in table 2. Column 1 shows results for our baseline model specifications (equation 1). 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 transfers from foreign countries. That is, countries that increase the stringency of tailpipe emissions standards receive more inward transfers of automotive ESTs through the patent system from innovating countries.

Column 2 presents results for the alternative model specification given by equation (2). Rather than absolute regulatory stringency alone, this estimation model

[15] 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..

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 hypothesis H1, column 2 shows a statistically significantly negative relationship for our regulatory distance variable, indicating that the number of newly-innovated automotive ESTs transferred 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 13.1 per cent.[16] 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 H1, 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. A possible explanation is that the introduction of more demanding regulation induces a shift of resources towards the innovation of higher performance ESTs designed for domestic compliance, fewer of which are suitable for markets elsewhere. 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 GDP per capita 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

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

positive effect, suggesting they function as complements rather than substitutes for new transfers. Changes in the strength of intellectual property rights (IPRs), on the other hand, only emerge as a statistically significant predictor of non-resident filings of automotive ESTs in column (2), being marginally insignificant in column (1).

6.2 The specificity of developed-developing country flows

Much of the debate on technology transfer has focused on the transfer of ESTs from developed to developing countries (Ockwell et al. 2011; Gallagher 2006; IPCC 2007). In order to explore these specific flows, as an alternative to pooling all cross-country transfers, we examine whether the above findings hold when restricting the sample to non-resident patents filed by OECD country residents in non-OECD countries.

As shown in table 3, we find similar results for our main explanatory variables compared to the main estimations. As before, absolute regulatory stringency has a significantly positive impact on inflows of patented ESTs (column 1), but the effect disappears once regulatory distance between countries *i* and *j* is included in the model (column 2), suggesting again that it is regulatory distance that matters rather than absolute regulatory levels in recipient developing countries. The results for control variables are similar with two exceptions: neither the stock of domestic relevant inventions nor GDP per capita in recipient countries matter for flows from developed to developing countries.

6.3 Consequences for total transfers

A key finding to emerge from section 6.1 is that the transfer of ESTs through the patent system is influenced by relative environmental regulatory stringency in country pairs. In particular, our results indicate that an increase in regulatory stringency will raise patent inflows from countries to which the recipient moves closer, but decrease them from countries that end up further away. What this suggests is that the impact of absolute regulatory stringency on the *total* number of patents transferred into country j in year t is a priori ambiguous and will depend on the country's regulatory position relative to the rest of the world.

We now turn our attention to this issue, which is of primary interest to policy makers. To do so, we move away from a dyadic (country-pair) estimation framework to a monadic (country) time-series panel, allowing us to directly analyze the effect of regulation on total transfers rather than transfers between country pairs. Of course, one would expect the results from the monadic framework to be consistent with the ones from the dyadic framework if both are properly specified. We define P_{jt} as the total number of patents received by country j in year t from all other countries i: $P_{jt} = \sum_{i \neq j} P_{ijt}$.

We then estimate the equation:

$$P_{jt} = \alpha_1 REG_{jt-1} + \beta \mathbf{X}_{jt} + \varepsilon_{jt} \qquad (3)$$

as the baseline model in the monadic estimation framework, where REG_{jt-1} measures the stringency of the regulation in country j, X_{jt} is a set of control variables that include, amongst others, a full set of country and year fixed effects, and ε_{jt} is the error term. Note that the set of control variables is the same as before, but the available inventions are now the sum of patents in all other countries, PAT_{-jt-1}. The PAT_{-it-1} variable, which captures transfers from other countries in the dyadic estimation framework, has no equivalent in the monadic estimation framework and is therefore dropped from the set of control variables. Equation (3) is estimated with a conditional fixed effects Poisson estimator with standard errors clustered on countries rather than the conditional fixed effects negative binomial estimator since the smaller number of observations in the monadic setting did not allow for cluster-bootstrapping of standard errors.

In order to explore how the effect of regulatory stringency varies according to the relative position of the recipient country vis-à-vis source countries, we define a dummy variable $FOLLOWER_{jt}$. The dummy is set to 1 if the recipient country's regulatory stringency is below the world's weighted average stringency. The weights represent the relative share of countries among all EST patents transferred globally in any one year such that the regulatory stringency of more important sources of non-resident patents counts more towards the global weighted average. We then interact the $FOLLOWER_{jt}$ dummy with absolute stringency, which allows us to estimate the effect of raising regulatory stringency in countries that are lagging behind the world's weighted average, versus countries that are not. This leads to the following alternative model specification for the monadic estimation framework, which allows us to test our second hypothesis:

$$P_{jt} = \alpha_1 REG_{jt-1} + \alpha_2 REG_{jt-1} \cdot FOLLOWER_{jt-1} + \alpha_3 FOLLOWER_{jt-1} + \beta \mathbf{X}_{jt} + \varepsilon_{jt} \qquad (4)$$

Results are shown in table 4. Column 1 first reports the estimation results for equation (3), that is, for regulatory stringency without distinguishing between followers and leaders. We find that an increase in absolute stringency has a positive, but insignificant impact on total patent inflows for the full country sample. However, in column 2, we estimate equation (4) and thus interact the FOLLOWER dummy variable with regulatory stringency. The coefficient for the regulatory stringency variable itself gives us the estimated semi-elasticity of regulatory stringency in countries that are at or above the world's weighted average stringency, i.e. where the FOLLOWER dummy variable is equal to 0. This coefficient is negative, but statistically insignificant. However, when the stringency in the recipient country is below average, then the estimated semi-elasticity is the sum of the regulatory stringency coefficient plus the coefficient of the interaction term. We find that tightening regulation by one unit increases total patent inflows by 13.6 per cent in laggard countries (-0.072 + 0.208 = 0.136). The effect in follower countries is statistically significantly different from the effect in leader countries and is significantly positive at the 11% level (thus, very close to conventional significance levels). Explicitly focusing on total inward patent transfers rather than bilateral transfers, we therefore confirm our previous finding that the effect of absolute regulatory stringency is conditioned by the recipient country's relative regulatory position.

6.4 Robustness tests

Results from a number of robustness tests for our dyadic framework estimations are reported in table 5. In the interest of space, we only report estimates for equation (2), which includes our main explanatory variable. In column 1, 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. 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 2, 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. In column 3, 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 analysing 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 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 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 4 by merging European countries into one single entity. The results are remarkably robust to this modification. In column 5, 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. In columns 6 and 7, we use alternative dependent variables, restricting the sample to fuel injection technologies in column 6 and on-board diagnosis (OBD) technologies in column 7. 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 international transfer 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 altogether. 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.

Consistent with this interpretation we find that regulatory tightening in countries whose domestic standards are below the world average raises the total number of patent filings of automotive ESTs by non-residents. Conversely, regulatory tightening in recipient countries whose standards are already more stringent than the world average does not lead them to receive more patented ESTs from abroad overall.

We caution against inferring too much from our findings. They only apply to newly-innovated ESTs purposefully transferred through the patent system and thus say nothing about the transfer of older technologies not covered by patents. Nor do they say anything about the cross-border diffusion of environmentally-relevant technology through knowledge spill overs (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 accelerating the inward transfer of new ESTs can be achieved by regulatory tightening, but only in countries which are regulatory laggards. This would generally include developing countries whose environmental regulatory stringency invariably lags behind the major 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 diagnosis 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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Table 1. — Summary statistics

	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 (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
Per capita income ($GDPPC_{jt}$)	9.34	1.04	6.17	10.91

Notes: N = 18741. GDP per capita is in constant 2000 US dollars. GDP per capita and all patent-based variables (except the dependent variable) are logged.

Table 2 — Main estimation results

Model	**(1)**	**(2)**
Reg. recipient (REG_{jt-1})	0.0596**	0.0068
	(0.0291)	(0.0315)
Reg. distance ($REGDIST_{ijt-1}$)		-0.1307***
		(0.0203)
Reg. source (REG_{it-1})	-0.0797***	-0.0831***
	(0.0277)	(0.0265)
Inventions (PAT_{it-1})	0.1060***	0.1111***
	(0.0184)	(0.0180)
Knowledge stock ($KPAT_{jt-1}$)	0.4030***	0.4028***
	(0.0516)	(0.0514)
Other countries' transfers (PAT_{-it-1})	0.2345***	0.2274***
	(0.0287)	(0.0292)
Patent protection (IPR_{jt})	0.1111	0.1224*
	(0.0737)	(0.0735)
Per capita income ($GDPPC_{jt}$)	0.2083***	0.1835***
	(0.0524)	(0.0518)
Observations	18741	18741
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 patents transferred 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.

Table 3 — Estimation results for developed-developing country flows

Model	**(1)**	**(2)**
Reg. recipient (REG_{jt-1})	0.0946**	-0.0741
	(0.0396)	(0.0649)
Reg. distance ($REGDIST_{ijt-1}$)		-0.1963***
		(0.0754)
Reg. source (REG_{it-1})	-0.1125*	0.0340
	(0.0675)	(0.0860)
Inventions (PAT_{it-1})	0.0188	0.0218
	(0.0257)	(0.0261)
Knowledge stock ($KPAT_{jt-1}$)	0.1925***	0.1999***
	(0.0517)	(0.0532)
Other countries' transfers (PAT_{-it})	0.2637***	0.2561***
	(0.0300)	(0.0306)
Patent protection (IPR_{jt})	0.0652	0.0458
	(0.1681)	(0.1706)
Per capita income ($GDPPC_{jt}$)	-0.1564	-0.1476
	(0.0999)	(0.0987)
Observations	4287	4287
Country-pairs	303	303

Note: *=significant at the 10% level, **=significant at the 5% level, ***=significant at the 1% level. The dependent variable is the number of patents transferred 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.

Table 4 — Total patent inflows

Model	**(1)**	**(3)**
Reg. recipient (REG_{jt-1})	0.1157	-0.0723
	(0.0828)	(0.0906)
*REG_{jt-1} * $FOLLOWER_{jt-1}$*		0.2083**
		(0.0834)
$FOLLOWER_{jt-1}$		-0.6461**
		(0.2523)
Inventions (PAT_{-jt-1})	0.0006	0.0006
	(0.0007)	(0.0006)
Knowledge stock ($KPAT_{jt-1}$)	0.4688***	0.4293***
	(0.1102)	(0.1075)
Patent protection (IPR_{jt})	0.7081**	0.6283**
	(0.3091)	(0.3050)
Per capita income ($GDPPC_{jt}$)	0.7464	0.5964
	(0.9316)	(0.8604)
Observations	675	675
Countries	45	45

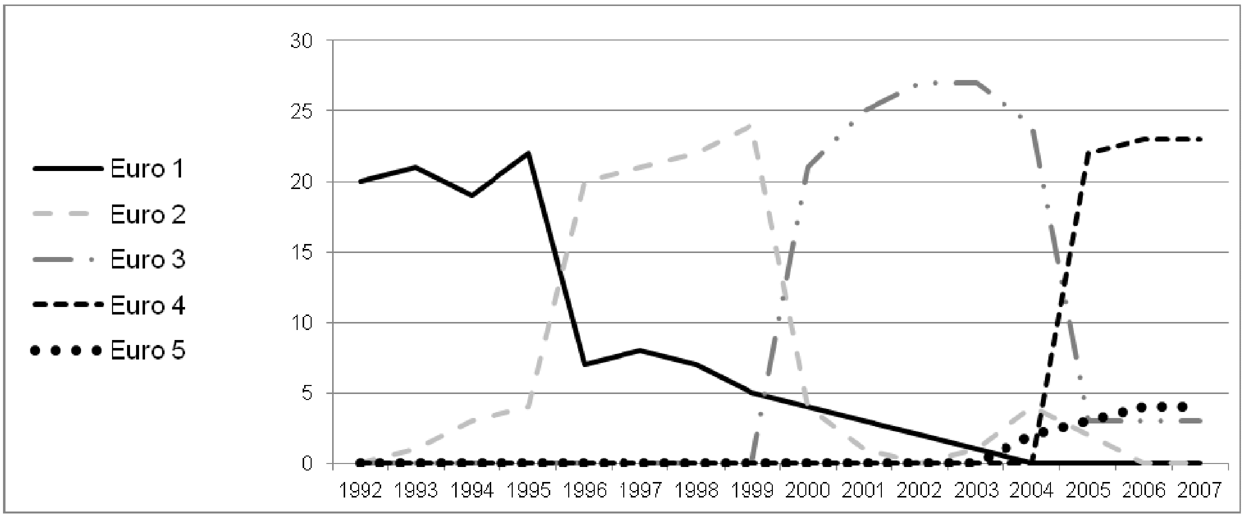
Note: *=significant at the 10% level, **=significant at the 5% level, ***=significant at the 1% level. The dependent variable is the number of patents transferred to country *j* in year *t* and subsequently granted. The models are estimated using a conditional country fixed-effects Poisson estimator and include a full set of year dummies (not reported for brevity). Standard errors robust and clustered by country reported in brackets.

Table 5 — Robustness tests

Model	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Reg. recipient	0.0034	0.0012	-0.0265	0.0301	-0.0448	0.0331	0.0275
(REG_{jt-1})	(0.0332)	(0.0284)	(0.0176)	(0.0588)	(0.0311)	(0.0410)	(0.0290)
Reg. distance	-0.1115**	-0.1063***	-0.0935***	-0.1471***	-0.2600***	-0.0829***	-0.1213***
($REGDIST_{ijt-1}$)	(0.0460)	(0.0184)	(0.0139)	(0.0470)	(0.0271)	(0.0287)	(0.0312)
Reg. distance squared	-0.0093						
($REGDIST_{ijt-1}$)^2	(0.0230)						
Reg. source	-0.0829***	-0.1060***	-0.0301*	0.0925**	-0.0524	-0.2237***	-0.2311***
(REG_{it-1})	(0.0263)	(0.0238)	(0.0170)	(0.0441)	(0.0471)	(0.0329)	(0.0409)
Inventions	0.1108***	0.0293	0.1775***	0.1650***	0.1907***	0.2635***	0.0967***
(PAT_{it-1})	(0.0179)	(0.0185)	(0.0213)	(0.0307)	(0.0195)	(0.0247)	(0.0213)
Knowledge stock	0.4037***	0.3714***	0.2766***	0.0006	0.3925***	0.3506***	0.4251***
($KPAT_{jt-1}$)	(0.0517)	(0.0491)	(0.0523)	(0.0544)	(0.0520)	(0.0542)	(0.0644)
Other countries' transfers	0.2275***	0.0797**	0.3900***	0.2696***	0.2030***	0.2904***	0.1603***
(PAT_{-it-1})	(0.0292)	(0.0342)	(0.0332)	(0.0376)	(0.0328)	(0.0435)	(0.0401)
All other transfers		0.2559***					
		(0.0193)					
Patent protection	0.1233*	0.1090	-0.0293	0.6246***	0.1674*	0.1907**	0.2554*
(IPR_{jt})	(0.0737)	(0.0677)	(0.0683)	(0.1581)	(0.0937)	(0.0912)	(0.1313)
Per capita income	0.1858***	0.1570***	0.2308***	-0.4064***	0.1657***	0.2105***	0.1218*
($GDPPC_{jt}$)	(0.0521)	(0.0500)	(0.0536)	(0.0645)	(0.0596)	(0.0602)	(0.0736)
Observations	18741	18741	28287	6480	15639	10527	11730
Country-pairs	1276	1276	1935	448	1066	718	798

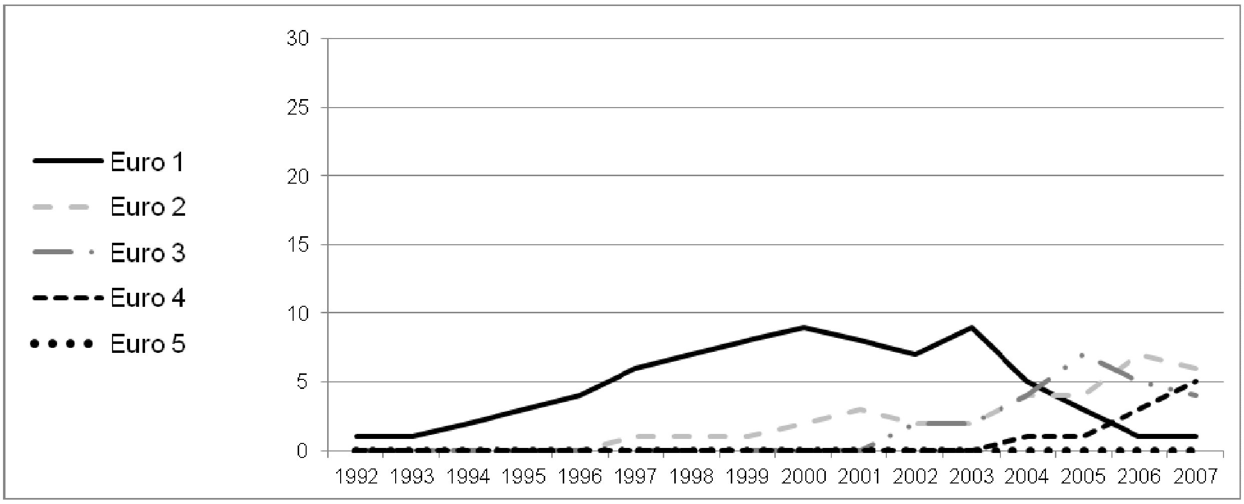
Note: *=significant at the 10% level, **=significant at the 5% level, ***=significant at the 1% level. The dependent variable is the number of patents transferred from country *i* to country *j* in year *t* and subsequently granted except in column 3, where the dependent variable is the number of patent applications transferred from country *i* to country *j* in year *t*. In column 4, EU15 countries are considered as a single entity. Column 5 drops Germany, Japan and USA from the sample. Columns 6 and 7 restrict the sample to patents related to fuel injection technologies and on-board diagnosis 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).

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



Source: Authors, based on Perkins and Neumayer (2012)

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



Source: Authors, based on Perkins and Neumayer (2012)