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Regulatory emission limits for mobile sources and the Porter hypothesis: a survey of the literature

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Abstract: This paper reviews the available evidence on the relevance of the Porter hypothesis for automotive emission standards. It focuses on two channels through which the Porter effect may operate. First, there is evidence that emission standards for cars have had important effects on innovation at different levels in the supply chain (the "weak" form of the Porter hypothesis), without discernible long-run negative effects in industry performance. However, there is no strong evidence either that regulations lead to an overall increase in productivity (the "strong" version of the Porter hypothesis). Second, there is relatively strong evidence that countries are more likely to have more stringent domestic vehicular emission standards if they export more automobiles and automobile components to countries which themselves have more stringent vehicular standards. There is also (mixed) evidence that countries which receive more inward foreign direct investment in the automotive sector are more likely to have more stringent domestic emission standards. This suggests that imposing strict emission standards may bring some "first mover advantages" to the leading countries, in line with the Porter hypothesis.

Keywords: Porter hypothesis, automotive emission standards, disruptive innovation, first-mover advantages, pollution control technology

JEL codes: F14, F21, L62, Q52, Q53, Q55, Q56

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1. Introduction

The use of cost-benefit analysis (CBA) in regulatory impact assessment is becoming a widely accepted practice. For instance, the European Commission requires its use whenever the most significant part of both costs and benefits can be quantified and monetised, and when there is a certain degree of choice as regards the extent to which objectives should be met (European Commission, 2009). In the United States, the origins of CBA can be traced back to the creation of the Office of Information and Regulatory Affairs under the Reagan administration, although some elements of economic evaluation of new regulations originated under the Nixon administration -

for a more extensive discussion, we refer to Renda (2011). Currently, Executive Order 13563[1] explicitly requires agencies "to use the best available techniques to quantify anticipated present and future benefits and costs as accurately as possible."

A key question is which costs and benefits should be taken into account in such a CBA. In the case of emission standards, these are typically:

- The "private" cost of emissions standards, which is the cost of abating emissions up to the level of the standard. This typically includes the technical compliance costs of manufacturers (which may -to some extent- be passed on to customers) or the foregone profits because some product lines are no longer profitable.
- The "social" benefits of emission standards are the environmental benefits of reduced air pollution, which can - to some extent - be expressed in monetary terms as well. The following environmental benefits are usually included in the assessment of the benefits of emissions standards: health impacts, greenhouse gas emissions, biodiversity impacts, impacts on buildings and agricultural yields[2].

Thus, in the logic of CBA, more stringent emission limits are justified whenever the total benefits of these new limits exceed their total costs.

However, some economists have argued that environmental regulation also brings "private" benefits to the regulated industry and could actually lead to increased competitiveness. This argument, whose origin can be attributed to Michael Porter (Porter 1991), can be summarized in two steps:

- Properly designed environmental regulation may spur innovation (the "weak" version of the "Porter hypothesis")
- In some circumstances this innovation may more than offset compliance costs and lead to increased competitiveness (the "strong" version of the "Porter hypothesis").

The "weak" version is relatively well accepted, insofar as the condition "properly designed" is fulfilled. The "strong version", however, certainly runs counter to the conventional wisdom that environmental regulation leads to increased costs for industry, and is very controversial. If true, the "strong version" implies that increased environmental standards are justified, even if the environmental benefits do not outweigh the direct compliance costs.

The "Porter hypothesis" has spawned a large literature. This is not the place to summarize this discussion, which focuses on the analysis of regulation of *stationary* sources– we refer the interested reader to the recent survey by **Ambec et al. (2013)**. Here, we wish to focus on studies that limit themselves to the regulation of exhaust emissions by *mobile* sources[3].

Let us just summarize some possible theoretical foundations for the hypothesis (see the recent survey by Ambec et al. 2013):

[1] http://www.gpo.gov/fdsys/pkg/FR-2011-01-21/pdf/2011-1385.pdf
[2] We refer the websites of the ExternE and NEEDS projects and EEA (2012) for a more extensive discussion of the monetary values that are typically used in CBAs for the European Commission.
[3] All the papers we have identified in our literature study confine themselves to the regulation of exhaust emissions of automobiles – none of them discusses off-road mobile sources. The application of the methods discussed in this paper to off-road applications could be an interesting subject for further research.

- Regulation may force investments that increase profits but are not otherwise undertaken by the management of the firm. This explanation assumes that managers do not always maximize profits. Possible explanations include that managers may be risk averse, resistant to change (and thus do not undertake investments that are out of their habits and routines), or rationally bounded (this is, limited by information or their cognitive abilities). Typically, these investments would be investments in energy efficiency or in waste management, where a “win win” situation is indeed possible. It is less obvious why this argument would hold for investments that lead to a reduction in the emissions of conventional pollutants. However, we shall see below that there is indeed some evidence that the introduction of more stringent emission limits for autos in the US has spawned periods where car manufacturers and their suppliers have ventured outside their core field of competence and have radically redesigned car engines. These changes in design have also benefited car drivers – it remains to be seen to what extent regulations have really triggered these changes or merely affected the timing of their introduction.
- A country can help domestic firms to obtain “first mover advantages” in the development of green technologies if the general tendency is towards even more stringent standards. Stringent environmental regulations can then be used to increase domestic firms’ market share. We shall see below that there is indeed evidence that, as the world is moving to even more stringent emission limits for autos, substantial knowledge transfers are taking place from frontrunner countries to laggard countries. Moreover, increased economic integration leads even more countries to adopt more stringent emission limits for competitive purposes.
- Firms often underinvest in R&D if their investment is partly captured by competitors, for instance because intellectual property law cannot protect all aspects of innovation. Regulations may force firms to invest more in R&D in general, and this could lead to improved competitiveness. We shall see below that the introduction of emission limits for automobiles has indeed significantly affected R&D efforts.

Our paper is structured as follows. First we provide a short history of worldwide automobile emission standards in order to clarify the context of the economic studies discussed in the paper. Second, we give an overview of the findings concerning a first channel through which the Porter hypothesis may operate: the effects of emission limits on R&D, productivity, innovation, costs and profitability. Third, we discuss the findings related to the possible sources of “first mover advantages”: the effects of emission limits on international knowledge transfers, trade flows and foreign direct investment.

2. A short history of automotive emission standards

2.1. Key steps in the US

Let us first consider the **US market**. More detailed discussions of the early developments can be found in Bresnahan and Yao (1984), Chen et al. (2004), Faiz et al (1996), Gerard and Lave (2005) and Hascic et al. (2009), which we have used as sources for what follows.

Auto emissions were first regulated in California in the early 1960s. The 1970 Clean Air Act required a 90 percent reduction in emissions of CO and HC from automobiles by 1975, and similar reductions in NO_x by 1976.

This was quite a drastic reduction, but the statute also granted the discretion to the Environmental Protection Agency (EPA) to delay implementation of the standards if the necessary technology and hardware did not become available. Gerad and Lave (2005) discuss the process in detail. First, in April 1973, the EPA granted a one-year delay of the 1975 HC and CO standards. Second, in June of the same year, the EPA granted a delay of the NO_x standards as well, and Congress extended interim HC and CO standards to 1977 and NO_x to 1978. The 1974 legislation authorized EPA to delay the standards for another year if necessary. Third, in 1975, the EPA extended interim HC and CO standards to 1978 in response to concerns about sulphate levels. Fourth, by 1977, it was no longer possible for the EPA to grant further delays. Uncertainty about the feasibility of the targets due to compliance costs[4] lead to an adjustment of the Act in 1977 to, amongst others, delay and relax some standards and impose similar requirements on trucks.

Several technological solutions were initially used to comply with these standards. Because catalyst were not ready in time for the 1972-73 model year automobiles, compliance was achieved with non-catalyst systems (engine detuning and axle ratio reductions) or with fuel injections. It has been claimed that these non-catalyst technologies may have substantially reduced automobile quality (see further for a more detailed discussion). By 1977 however, only about 10% of automobile models complied without a catalytic converter. By 1980-81 breakthrough technologies such as electronic engine control and fuel injection provided higher vehicle quality, but at a higher cost than incremental technology such as conventional systems with larger catalysts.

Between the 1977 Clean Air Act Amendments and 1990, regulations remained virtually unchanged. The 1990 Clean Air Act amendments mandated even stricter standards for light-duty and heavy-duty vehicles (for HC, CO, NO_x and particulate emissions), and also regulated emissions from non-road vehicles and mobile equipment for the first time.

The US established Tier I standards for HC and NO_x in 1994. From 1994 till 2003, NOx standards for diesel engines were a bit more lenient than for gasoline engines. Tier II standards (from 2004) on are fuel neutral, with the exception of a few temporary options (Delphi 2014). The National Low Emission Vehicle Program (NLEV) enacted in 1997 was designed to adopt the stringent California LEV program nationwide. It would continue through 2003, after which it would be replaced by the new Tier 2 standard.

Finally, on March 29, 2013, the US EPA signed a proposed rule introducing Tier 3 emission standards for light-duty vehicles.

2.2. Key steps in Japan

Japan introduced the Air Pollution Control Law in 1968. Initially, only CO was regulated. From 1978 on, HC and NO_X also became subject to regulation. The 1992 Motor Vehicle NOx law also specifies performance standards for NO_x emissions from *in-use* vehicles, not just new ones. The regulation of NOx has gradually become more stringent. Since 1997, PM emissions from diesel vehicles (which were, until then, either exempted or weakly regulated) are also controlled (Managi et al. 2010).

2.3. Key steps in Europe

Until the mid-1980s, motor vehicle emission regulations in **Europe** were developed by the UN Economic Commission for Europe (ECE) for adoption and enforcement by individual member

[4] This adjustment took place despite concerns that Chrysler was stalling. Whether or not this was deliberate, some authors have argued that Chrysler invested little in R&D at the time – see Gerard and Lave (2005) for a detailed discussion.

countries. However, since the 1990s, the ECE no longer promulgates standards that have not been agreed first by the EU (Faiz et al 1996), even though other ECE activities may still precede European standards[5].

The first step in European regulatory measures was Council Directive 70/220/EEC from 1970 which first specified the maximum limits for CO and HC vehicle emissions. Subsequently, Council Directive 74/290/EEC tightened the CO and HC standards, Commission Directive 77/102/EEC added emission limits for NO_X and Commission Directive 78/665/EEC further tightened the limits.

In the mid-1980s, several EU countries introduced economic incentives to encourage the use of low-pollution vehicles or adopted mandatory vehicle standards and regulations. European legislation further developed in parallel. Council Directive 83/351/EEC imposed stricter CO standards and introduced limits on the combined HC + NO_x emissions; Council Directive 88/76/EEC provided additional restrictions on NO_x emissions separately; and Directive 88/436/EEC introduced standards for PM emissions (Hascic et al. 2009).

In 1990, the European Council of Environmental Ministers ruled that all new, light-duty vehicles sold in the EU in 1993 meet emission standards equivalent to 1987 US levels. They also proposed future reductions to reflect technological progress (Faiz et al 1996). In 1992, Council Directive 91/441/EEC replaced the Annexes to Directive 70/220/EEC and introduced the Euro 1 performance standard. Since the 1996 Euro 2, there have been different standards for diesel and gasoline vehicles, both of which have become progressively stricter (Hascic et al. 2009). Regulation 715/2007/EC introduces the Euro 5 (2008/9) and Euro 6 (2014) standards for light passenger and commercial vehicles.

2.4. Perspectives

The literature of emission standards usually distinguishes technology-forcing from technology-following standards (see for instance **Faiz et al. 1996**):

- **Technology-forcing** standards are at a level that, though technologically feasible, has not yet been demonstrated in practice. Manufacturers must research, develop, and commercialize new technologies to meet these standards.
- **Technology-following** standards involve emission levels that can be met with demonstrated technology. The technical and financial risks involved in meeting technology-following standards are therefore much lower.

Faiz et al. claim that technology-forcing emission standards have provided the impetus for nearly all the technological advances in the field. Back in 1996, Faiz et al. concluded that the United States had often set technology-forcing standards whilst Europe had generally adopted technology-following standards. According to Faiz et al., much of this lag had been caused by the complex, consensus-based approach to standard setting used by the ECE (see above). The shift to an increased use of qualified majority voting in the Council had however facilitated the adoption of more stringent emission standards[6]. Faiz et al acknowledged that, by 1996, the stringency of the most recent EU emission standards had come close to that of the US standards.

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[5] Personal communication from AECC.

[6] It should also be added that, as illustrated above, the US EPA is granted considerable discretion to delay implementation if the necessary technology does not become available. In the EU, because the limits are set by the co-decision procedure, it would be a much more difficult (and lengthy) process to revise standards if

Back in 1996, Faiz et al also argued that, as the US standards were used by many other countries and were considered a benchmark for national standards around the world, they were treated a de-facto international standard. In their more recent survey of worldwide emission standards (see further for details), Perkins and Neumayer (2012) however concluded that the vast majority of developing countries have emulated EU standards. Thus, the situation has dramatically changed in this respect.

This historical role played by the US partially explains why most studies until now focus on the economic effects of tightened regulations in the US.

In the current framework, it is difficult to compare European and US emission limits, because the test cycles are different. In the US, the same emission limit applies to diesel and the gasoline cars. In the EU, the standard for diesel cars is less stringent than for gasoline cars, as a transitional measure to give manufacturers the time to develop less polluting diesel technologies that can be exported to the rest of the world. As a result, US emission limits for diesel are more stringent than European ones (personal communication from AECC).

Also, it no longer holds true that innovation is mainly driven by US standards. For instance, SCR for heavy-duty vehicles were first introduced in the EU. Until now, the share of diesel light-duty vehicles in the US has remained low. While this may be partly explained by historical experiences with diesel cars, this "low diesel share" equilibrium also follows from the limited refinery capacity for this fuel (which, in turn, is maintained because of the limited interest in diesel technology). However, with even more stringent emission limits for diesel vehicles in the EU, and the growing share of diesel technologies in the US, it is possible that we will observe transfers of diesel technologies from the EU to the US in the future (personal communication from AECC).

3. The impact on innovation and costs

The first study on this subject that we are aware off is **Bresnahan and Yao (1985).** Bresnahan and Yao show that, immediately after the coming into force of the Clean Air Act Amendments (CAAA) of 1970, the nonpecuniary compliance costs (mostly performance disadvantages of the new vehicle) were as large as the manufacturer's costs plus the foregone fuel economy. However, Bresnahan and Yao also argue that since 1973, the rate of technological progress in mobile-source pollution control has been rapid, and that, in most time periods, the technological advance has offset the increasing stringency of emission standards.

For the next comprehensive discussion of the innovation effect of automobile emission standards, we have to take a twenty year jump ahead. In 2004, the California Air Resources Board asked the Institution of Transportation Studies at the University of California at Davis to analyse the historical effects of previous regulations. The researchers have analysed in detail two time periods when the emission standards in US were sharply tightened and were known to require costly new emission control technology (1973-1975 and 1979-1981).

Their findings were summarized in a series of complementary publications (see **Chen et al. 2004, Burke et al. 2004, Sperling et al. 2004**), which can be summarized as follows.

First, although the first response in the 1970s involved a downsizing of cars, the automakers eventually responded to stricter standards primarily with technological solutions - as opposed to

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implementation turns out to be problematic. Therefore, feasibility is being given a greater weight at the time of adoption (personal communication from AECC).

modifications in vehicle attributes such as size or performance. The periods of the most rapid technology change were the second half of the 1970s[7] and the first half of the 1980s[8].

Second, the manufactures made other complementary technological changes including the installation of fuel injection, on-board diagnostics, and computer control technologies.

In general terms, emission control devices produce several types of feedback in the design of the vehicle:

- On the negative side, the addition of control technologies increases the vehicle weight as well as required auxiliary devices, such as air pumps.
- On the positive side, the use of unleaded gasoline increases the life of exhaust system and spark plugs (reducing maintenance costs). Moreover, the use of computer controls allows better combustion control, higher energy efficiency and performance. Tightened emission standards may also have led to the introduction of better batteries.

Third, very little is known on the actual compliance costs because this is considered proprietary information by auto manufacturers. However, vehicle regulations had little discernible effect on industry performance and activities. While compliance costs may have been significant, they only represent a modest part of overall vehicle cost increases. Moreover, whatever the actual compliance costs, the disruptive impact of new regulations in the 1970s was larger than it would be now because the usual planning cycle at that time ranged between five and seven years.

The authors conclude that the adoption of aggressive requirements in the 1970s *may* have aided the US auto industry by forcing it to innovative earlier than it would have otherwise. This conclusion provides support for a "weak" version of the Porter hypothesis and is certainly not in contradiction with a "stronger" version. However, they do not provide hard evidence for this claim.

In a paper for the European Commission (DG ENV), **Kuik (2006**) has addressed the innovation dynamics induced by environmental policy in the automotive industry. Kuik reminds the reader that there can be large differences in the speed and extent of international diffusion of environmental innovations in the car industry. The catalytic converter for instance diffused quickly from the US to other regions, but European innovations in fuel efficiency (especially in diesel technology for passenger cars) did not affect the US market very much. However, the focus of his paper is on car fuel efficiency programs rather than on the control of polluting emissions, and its relevance for our subject is limited.

Lee and Veloso (2006) have investigated to what extent periods of changes in emission limits affect the relative share of "component innovation" and "architectural innovation" in the R&D output of assemblers and suppliers, respectively.

To do so, they have looked at the patenting behaviour by assemblers and suppliers in US automobile industry in the period from 1970 to 1998. Using patent data from the US Patent and Trademark Office (USPTO), they have identified successfully applied patents in the field of automotive emission control systems.

They used two approaches to generate the relevant patent set: an abstract-based keyword search and a class-based search. For the former, they selected seven different keywords: catalytic converter, emission, automobile, catalysts, pollution, exhausts, and engine. In both approaches, patents were pulled for each subclass, duplicate patents were eliminated, relevant patents were

[7] Mainly the introduction of the two-way oxidation catalytic converter.

[8] Corresponding to the introduction of the three-way oxidation/reduction catalytic converter and complementary new engine technologies.

identified by reading through the abstracts and the "Claims" portion and assignee sections were examined if necessary to sort out technologies unrelated to automotive emission controls.

Patents for automotive control systems where then divided in patents for "component innovation" and for "architectural innovation".

- Lee and Veloso associate "component innovation" with clearly identifiable physical portions of the system. They have classified the following innovations as "component innovations": advanced catalysts, catalyst support materials, gas sensors for electronic feedback emission control technology, metal housing from manufacturing technology, and hydro-carbon (HC) absorber materials designed to reduce HC emission during the cold start from thermal control technology.
- According to Lee and Veloso, 'architectural innovation' integrates components into a whole system. This includes: the majority of innovations from electronic feedback emission control technology such as air-to-fuel ratio control, electronic exhaust gas recirculation (EGR), and catalytic converter efficiency monitoring; dual-bed converter design, exhaust system design, cold-start up system, and electrically heated converter system.

Next, Lee and Veloso divide the period from 1970 to 1998 in 5 sub-periods, each corresponding to periods of either important *changes* in the regulatory pressures (mainly Amendments to the Clean Air Act) or of relative stability.

Using econometric tools, they then show that, in periods of changes in the stringency levels, assemblers tend to expand their knowledge base in components: there is a higher share of patents in component innovation than in "stable" periods. Conversely, periods of changes in stringency levels lead suppliers to expand their knowledge base in product architecture: there is a higher share of patents in architectural innovation than in "stable" periods.

Assuming that the core competence of assembling firms lies in the architecture of a vehicle, and the core competence of suppliers in the components, this research suggests that changes in the stringency of emissions standards have led firms to invest in knowledge that does not normally fall in their core field of competence. One possible explanation for this behaviour is the need to develop a common language to facilitate more effective information exchanges between partners involved in inter-firm product development when radical changes are needed.

Lee and Veloso conclude that both automakers and component suppliers introduced rather novel systems that resulted from important knowledge investment and that had a large impact on internal organisational dynamics. Their research thus provides strong evidence in favour of the "weak" version of the Porter hypothesis.

Hascic et al. (2009) is, to the best of our knowledge, the first study with a more international scope. They analyse patenting activity in automotive emission-control technologies for a cross-section of OECD countries for the period 1978-2005.

They have used the International Patent Classification (IPC) system of the World Intellectual Property Organisation (WIPO) to identify patent classes that match automotive emission-control technologies. These codes have then been broadly categorised into the two major technology groups: 1) those that relate to improvements in engine (re)design; and 2) those that treat pollutants after they are produced but before they are released into the atmosphere.

Next, they have extracted data on patent applications deposited at the European Patent Office (EPO) from the OECD Patent Database. They have then constructed patent counts disaggregated by source country, earliest year of application within a given patent family, and technology type. The descriptive data clearly show that Japan and Germany have the highest patent counts, followed by the United States.

In order to represent the effects of regulation, they have created proxy variables for the emission standards in three key regions of the world (US, Europe and Japan) since 1981. They expected regulatory developments in each of these regions to have an impact on inventors in all countries.

Hascic et al. find that both domestic and foreign environmental regulations, as well as fuel prices, played an important role in terms of encouraging innovation with respect to the pollution emissions of motor vehicle technologies.

"Integrated" innovations (such as on-board diagnostics) which capture both private (for instance reduced fuel consumption) and public (for instance less emissions of GHG) benefits are determined both by gasoline prices and those policies which sought to encourage the use of technologies which yield both types of benefit. However, in the case of post-combustion technologies (which only yield public benefits), it is primarily regulatory standards which drive innovation. Gasoline prices and the general rate of innovation have little influence. Again, this research provides evidence in favour of the "weak" form of the Porter hypothesis.

Somewhat surprisingly, Hascic et al. also find that foreign regulations can have a greater influence on domestic innovation than domestic regulations. One possible explanation may be that manufacturers can better anticipate new domestic regulations (thus reducing the "shock" effect of the new regulation), and can also (to some extent) influence them.

Lee, Veloso and Hounshell (2011) can be considered as a companion paper to Lee and Veloso (2006). The main difference is that the focus in this paper is on the absolute number of patent applications, rather than on the shares of "component innovation" and "architectural innovation". However, the methodology for the identification of the relevant patents is the same.

Using econometric techniques, they show that, between 1970 and 1998, technology-forcing auto emissions regulations in US lead both automakers and component suppliers to innovate and introduce more advanced control techniques. The authors emphasize that their study is the first to show this effect for performance-based regulations rather than technology-based regulation. The strongest innovative reaction happened when the government enacted the two most ambitious requirements (the 1970 and the 1990 CAAA). The study confirms that the regulation did not only affect innovation by the assemblers, but also by the supplying firms. The authors conclude that stringent regulations can lead to radical technological change (developing the automotive catalytic converter) rather than incremental innovation (such as modifying the existing engine structure).

Lee, Veloso and Hounshell shed also some light on broader international impacts. In the early phase of regulatory regime (1970 to 1973), stringent regulations temporarily induced domestic US firms to become more innovative than foreign firms that operated in the local US market[9]. However, this impact no longer persisted in the early 1990s. Note that, as the time perspective taken is different, this finding is not inconsistent with the conclusions reached by Hascic et al.

Managi et al. (2011) empirically analyse the effects of environmental regulation on R&D expenditure and productivity in the Japanese auto industry. They use panel data from 1990 to 2002 of 75 firms, including assembling firms, parts manufacturing firms and body manufacturing firms. Environmental policy stringency is measured as the "regulation intensity", this is the ratio of the emission standard for each pollutant for each vehicle type and production year to the emission standard for diesel trucks in 1996. For the firms manufacturing parts and vehicle bodies, they construct "stringency variables" based on the values of these variables for the assembling firms

[9] By 1977, however, the share of foreign sources (mainly German and Japanese) in the number of patents granted in the US for vehicular air pollutants had risen to 66% (Lanjouw and Mody 1996).

they cooperate with. Note that their dependent variable is R&D expenditure rather than patent output.

They find that exhaust emission regulation stimulates the R&D *expenditure* of firms in auto industry; this effect is larger for assembling firms than for parts manufacturing and body manufacturing firms. This confirms the “weak” form of the “Porter hypothesis”.

They also show that increases in R&D raise the productivity of the firms and that stricter regulation does not reduce the effect of R&D on productivity. However, regulation dos not directly raise the productivity in the auto industry. Thus, in this case, no support is found for the “strong” version of Porter hypothesis.

4. International technology diffusion

In this section, we look at the available evidence concerning the international diffusion of emission control technologies for mobile sources. One key indicator in this field are non-resident patent filings.

Indeed, 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 (Dechezleprêtre et al. 2012). Medhi (2006) argues that, as there are costs associated with applying for and maintaining a patent in force, few patentees seek protection abroad. Therefore, foreign patents indicate protection in an existing or potential *export* market.

Medhi (2006) is, to the best of our knowledge, the first paper that tackles the international spillovers of emission control technologies in the automobile sector. She asks whether innovations in pioneer countries enable developing countries to regulate more quickly than they otherwise would. To do so, she constructs a database of patent data from the Delphion database. She uses inventor country to identify the source of the technologies, and uses the International Patent Classification (IPC) codes to identify the relevant patents.

Medhi shows that, in pioneer countries, regulations precede technological change. In contrast, technology advances in developing countries follows technology ‘already on the shelf’. Most such foreign technology originates in the “pioneering” countries: Japan, USA and Germany.

Dechezleprêtre et al. (2012) examine the impact of environmental regulation on the international diffusion of new technology through the patent system.

Dechezleprêtre et al. argue that the automobile industry is a competitive one which, in many segments of the market, is highly price-sensitive. 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. According to Dechezleprêtre et al. , 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.

Dechezleprêtre et al. have constructed a panel data set that combines the level of motor vehicle emissions product standards in 72 countries between 1992 and 2007 with patent fillings in corresponding automotive emission reduction standards. National emission standards are all expressed in terms of European Union (EU) standards equivalent. They 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 them to measure cross-border technology flows. Patent data were obtained from the World Patent Database (PATSTAT) maintained by the European Patent Office. They have 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. Information about the patent office that receives the patent was used to identify countries to which a particular invention has been transferred.

In line with the Porter hypothesis, Dechezleprêtre et al. argue that inventors in early-regulating source countries (such as Japan, Germany and the US) are likely to possess a competitive advantage vis-à-vis potential competitors in follower countries, stemming from the fact that their pre-existing compliance technologies benefit from dynamic scale economies and learning effects. This, in turn, would provide an incentive for inventors in source countries to transfer their technologies to recipient countries which adopt similar standards to their own.

Dechezleprêtre et al. find robust evidence that follower countries receive more emission reduction technology patents where their regulatory standards become closer to those in inventor countries. They argue that a possible explanation for this observation is that regulation driven demand for emission control technologies is more likely to be supplied by foreign innovators who have already innovated compliance technologies in response to similar standards in their home countries.

However, they also find that regulatory tightening in recipient countries whose standards are already more stringent than the world average does not lead them to receive more patented emission control technologies from abroad.

In a closely related paper, **Perkins and Neumayer (2012)** verify whether, in the case of automobile emission standards, they can confirm the hypothesis that economic integration may lead to the ratcheting upwards of regulatory standards towards levels found in higher-regulating jurisdictions (the so-called "California effect").

As Perkins and Neumayer explain, there are two possible sources for "ratcheting-up":

- **Trading-up via exports**. Under the rules of the World Trade Organisation, national governments can ban imports that do not comply with environmental products standards. Therefore, if firms have the knowledge how to comply with standards in their export markets, they will gain if their government also imposes similar standards in their home market. Indeed: (a) if they can sell the same product to their home market as to their export market, this will allow them to realise economies of scale (b) stricter standards in their home markets provides them with a competitive advantage vis-à-vis competitors in their home market lacking the necessary competences. We can expect these firms to lobby for tighter environmental standards. It should be noted that the "less regulated" market in the current context usually refers to a "developing" economy. However, Perkins and Neumayer also refer to evidence that the German support for tighter standards in the EC was at least partly due to the fact that German car makers were already producing vehicles that complied with the more stringent emission limits in the US, a major export market.
- **Investing-up via inward foreign direct investment (FDI)**. The starting point for this argument is that many of the world's transnational corporations originate or at least operate in high-regulating developed economies, and therefore are able to comply with

the most stringent standards. Moreover, these companies tend to transfer their "more-than-compliant" technologies to their foreign affiliates and subsidiaries, even in countries that are subject to less stringent regulations. Possible reasons include the cost of re-engineering technologies and possibly the wish to avoid criticism from civil society. However, in order to be able to compete with "compliance-only" local firms, these TNCs will then lobby for the upwards harmonisation of environmental standards.

In order to test their hypothesis, Perkins and Neumayer use the international panel set with the level of motor vehicle emissions product standards discussed in Dechezleprêtre et al. (2012).

They test two hypotheses:

- Countries are more likely to have more stringent domestic vehicular emission standards where they export more automobiles and automobile components to countries which themselves have more stringent vehicular standards. This hypothesis is confirmed by the data.
- Perkins and Neumayer hypothesise that countries which receive more inward FDI in the automotive sector are more likely to have more stringent domestic emission standards. In this case, the hypothesis is only partially confirmed. However, this absence of convincing evidence can be at least partly attributed to shortcomings in the available time-series.

Saikawa and Urpelainen (2014) propose an alternative approach to understanding the relationship between FDI and emission standards in developing countries. The starting point of their analysis is that China adopted Euro 1 standards in 2000, at a time when Chinese automobile export capabilities were still very limited. Therefore, in this specific case, they do not think that the "trading up via exports" hypothesis is a credible explanation for the introduction of emission standards that were relatively stringent for a developing country at that time.

Saikawa and Urpelainen propose two alternative but interrelated explanations for this move. A first explanation is related to the "public good" nature of innovation: if firms cannot capture entirely the benefits of innovation[10] , they will tend to underinvest in research and development. By imposing relatively stringent emission standards on domestic firms, the government forced them to develop new technologies, overcoming this "public good" problem. Second, China required foreign companies engaged in the production of automobiles, motorcycles and engines to own at most 50% of a joint venture with a Chinese partner. Moreover, it imposed specific requirements to enhance technology transfer to the Chinese partners. The introduction of Euro 1 emission standards would then force foreign companies to introduce more advanced existing technologies in joint ventures, which would then eventually be transferred at least partly to the Chinese partners. This would in effect reduce the technical compliance cost to the Chinese economy. Moreover, it would enhance the Chinese economy's productivity and international competitiveness.

Such a strategy can only work in countries if it is acceptable to the foreign companies that are forced to transfer their technologies. Saikawa and Urpelainen hypothesize that this is the case if (1) the domestic consumer market in the developing country is lucrative enough for automobile FDI (2) the cost of the forced technology transfer is not too high.

Saikawa and Urpelainen use a panel data set comprising the years 2000-2006 and 92 countries to test which variables affect the probability that a country will for the first time adopt automobile

[10] For instance, because intellectual property rights are not perfectly protected.

emission standards. Their model confirms that automobile FDI has a strong positive effect on the probability of adaption of emission standards[11], while other explanatory variables yield less robust relations.

In short, Saikawa and Urpelainen have identified another channel through which high domestic emission standards are likely to be adopted in third countries. However, as this mechanism involves technology transfers to foreign producers, this mechanism is not necessarily in the best interest of domestic producers.

5. Conclusions

From this literature survey, we can draw the following main conclusions:

- Historically, emission standards for cars have had important effects on innovation at different levels in the supply chain (assembling firms, but also component suppliers). Moreover, important changes in the stringency levels have led to investment in better communication between assemblers and suppliers, and have had a large impact on internal organisational dynamics. There is also evidence that little innovation in post-combustion technologies would have taken place in the absence of regulatory standards. All in all, stringent changes in regulation seem to have led to radical technological change (such as developing the automotive catalytic converter) rather than incremental innovation (such as modifying the existing engine structure).
- When emission standards were first introduced in the beginning of the 1970s, initial compliance costs (including decreased vehicle performance) turned out to high. However, compliance costs have decreased over time due to learning effects. Very little hard evidence is available on the actual costs, but past regulations seem to have had little discernible long-run effects in industry performance.
- The innovation needed for regulatory compliance has led to complementary technological changes with beneficial side-effects for users as well, such as reduced maintenance costs, better combustion control and higher energy efficiency. There is however no strong evidence that these side-effects would not have taken place in the long run anyway – it could be that the main effect of the emission standards has been an acceleration of innovations that were bound to take place.
- The impact of foreign regulations on domestic innovation is somewhat mixed. There is evidence that stringent emission limits in the US in the beginning of the 1970s have had a disproportionate initial effect on domestic innovation, but that this effect has rapidly waned over time. Evidence on the effects of regulatory regimes since the 1990s suggests that they affect innovation in exporting countries more than in the domestic industry.
- However, there is no strong evidence that regulations lead to an overall increase in productivity (the “strong” version of the Porter hypothesis). In most cases, the lack of evidence is simply due to the fact that the hypothesis has not even been tested, probably

[11] This is not inconsistent with the findings of Perkins and Neumayer: Saikawa and Urpelainen only look at the probability of adopting standards for the first time, and do not consider increases in the stringency of these standards through time.

due to a lack of data. However, the one test we are aware off has rejected the "strong" version.

- In the countries that have pioneered stringent emission standards, regulations have preceded technological change. Developing countries mostly use "off the shelf" technology that originates from pioneering countries. When regulatory standards in follower countries become more stringent, this leads to knowledge import in these countries in the form of non-resident patent filing.
- Regulatory tightening in recipient countries whose standards are already more stringent than the world average does not lead them to receive more patented emission control technologies from abroad. Thus, for these countries, increasing the stringency of the standards could lead to an increase in net domestic innovation.
- There is relatively strong evidence that countries are more likely to have more stringent domestic vehicular emission standards if they export more automobiles and automobile components to countries which themselves have more stringent vehicular standards. There is also (mixed) evidence that countries which receive more inward FDI in the automotive sector are more likely to have more stringent domestic emission standards. Moreover, FDI is also a strong predictor that a country will for the first time adapt emission standards.

Of course, there are some limitations to the existing literature.

First, all these studies focus exclusively on the automobile market. It could certainly be worthwhile to undertake similar studies for the heavy-duty market and for the off-road market, but this would require an important investment in data collection and interpretation.

Second, all these studies, inevitably, evaluate historical events. They do not demonstrate that further increases in the stringency of emission limits would have the same effects. However, the 1970 CAAA was already very disruptive at the time, and the vast majority of engineers had initially no idea how they could meet these standards (see for instance Chen et al. (2004) and Gerard and Lave (2005)). The studies we have summarized here convincingly show that the disruptive nature of these regulations have led to radical innovations in organisation and design, and eventually (with some delays compared to the initial time-table) to compliance.

Third, the policy implications of this survey need to be formulated with care. The EU currently has a worldwide leading role in setting automobile emissions standards. If the EU maintains this leading position, there is empirical evidence that increasing the stringency of emission standards over time should lead the EU's most important trading partners in the developing world to also increase their stringency levels. This could in turn lead to technology flows from the EU to the rest of the world, and could bring benefits to the European automobile industry and its suppliers in the long run. The question whether these benefits outweigh the initial compliance costs has however not been answered yet. For instance, if the adoption of emission standards in third countries goes hand in hand with forced technology transfers to domestic firms, the gains will be less certain.

In short, in the context of automotive emission standards, the "strong" version of the Porter hypothesis has not yet been the subject of formal empirical testing. Performing such tests is an important topic for further research.

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