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Effects of Environmental Policy on the Type of Innovation: The Case of Automotive Emission-control Technologies

by

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Introduction

Automotive emissions are among the major sources of local air pollution. The major pollutants emitted by motor vehicles include carbon monoxide (CO) and nitrogen oxides (NO_x). In OECD countries, car emissions account for 55% of CO and 36% of the ozone-causing NO_x emissions.[1] Other automobile pollutants include hydrocarbons (HC) and particulate matter (PM), contributing 21% and 12% respectively to air emissions in OECD countries (OECD, 2007).[2] Given the relatively large contribution of automotive emissions to overall air pollution, reducing the amount of emissions generated by motor vehicles can contribute significantly to improving local air quality.

There is a relatively limited body of literature that examines the links between environmental regulation and technological innovation and diffusion empirically. Earlier research on the induced innovation hypothesis used patent data in rather broad terms – either by analysing the overall patenting activity or by environmental patenting in general (*e.g.* Lanjouw and Mody, 1996; Jaffe and Palmer, 1997; Brunnermeier and Cohen, 2003). More recently, several studies adopted a more specific focus. For example, some studies explored the effects of higher energy prices on innovations in energy-efficient technologies for stationary sources (*e.g.* Popp, 2002) and mobile sources (*e.g.* Crabb and Johnson, 2007). The study by Crabb and Johnson examines the effects of motor fuel prices on patent activity in the field of energy-efficient automotive technology. However, effects of environmental policy on technologies which are explicitly emission-reducing are not addressed. Few papers have studied innovation specifically related to air quality control (*e.g.* Taylor *et al.,* 2003; Popp, 2003), and those which exist have analysed innovation related to SO_2 and NO_x regulations for stationary sources.

Finally, there are few available cross-country studies (*e.g.* De Vries and Withagen, 2005; Popp, 2006; Popp *et al.,* 2007). For example, Popp (2006) explored the effect of environmental regulations on both national and international technological innovation and diffusion in air pollution control for coal-fired power plants and found that domestic regulation plays a major role in fostering innovative activities in the home country. Johnstone *et al.* (2008) examined the role of domestic policy design on renewable energy patents for a broad cross-section of OECD countries. Popp *et al.* (2007) studied innovations in the pulp industry and found that foreign consumer pressure can be an effective means of inducing innovation. One key difference between these industries is that the final product is traded in the case of the pulp and paper industry, so that consumer demand for environmentally-friendly paper can influence production across borders. In contrast, most electricity is not traded across borders, making domestic regulation more important.

This paper examines patenting activity in automotive emission-control technologies for a cross-section of OECD countries in the period 1978-2005. We 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. However, the role played by these two factors depends very much on the type of technology induced. In particular, fuel prices have been key to the development of "integrated" abatement technologies, while regulatory standards have been more important for the development of post-combustion technologies. This result reflects the fact that innovation with respect to environmental technologies results in both private (*i.e.* increased fuel efficiency) and public (*i.e.* reduced emissions) benefits, while in the case of post-combustion technologies the benefits are purely public.

The structure of the paper is as follows. The next section discusses the different types of automotive emission-control technologies and introduces the data on patenting activity in this field, followed by a section providing an overview of the regulations of the automobile sector in the United States, Japan and Europe. The penultimate section presents the empirical analysis of the effects of regulations and fuel prices on patenting activity and the final section summarises the findings and concludes.

Technological innovation in automotive emissions control

Technology overview

Automotive emission-control technologies comprise all technologies that are used to reduce pollutants produced and released into the atmosphere by automobiles. Based on the point of emission, pollutants fall broadly into two categories: tailpipe (or exhaust) emissions (*e.g.* CO, HCs, NO_X, PM) and evaporative emissions (*e.g.* VOCs). Tailpipe emissions are produced as a by-product in the (imperfect) combustion of fuels to power the vehicle and are released from the vehicle's exhaust system. Evaporative emissions are produced as a result of the evaporation of fuel due to heating of the vehicle or release of vapour while refuelling.

There are four primary methods used to control tailpipe emissions: increasing engine efficiency, treatment of emissions emitted, increasing vehicle efficiency, or increasing driving efficiency. This paper is concerned only with innovations related to the former two types of technologies, namely those that increase engine efficiency and those that involve post-combustion devices. The latter two types of control methods depend on non-technological aspects (*e.g.* driving techniques, levels of congestion) or on material improvements (*e.g.* light-weighting, aerodynamic design). Consequently, these issues are not considered here in this paper.

The type of pollutant and its volume are to a great extent determined by the type of vehicle engine installed (*e.g.* spark-ignition and diesel engines) and the type of fuel it uses. While the different types of engines require different control technologies, the approaches can be broadly classified in two groups. Reductions in exhaust emissions can be achieved by *i*) (re)designing the engine or by changing conditions under which combustion takes place and *ii*) treating pollutants before they are released into the atmosphere (post-combustion). It is important to note that the impacts of engine design are not always exclusively environmental. For example, changes in engine design are often motivated by the objective to increase engine power or improve fuel efficiency, while also reducing exhaust emissions. Some emissions control requirements have also resulted in improved fuel quality and fuel efficiency.

Post-combustion technologies allow reaction with and treatment of the remaining emissions. Such technologies are an important component of emissions control strategies because reductions in the amount of pollutants generated due to advances in engine design, although continually improving, are generally considered insufficient to meet emissions goals. Table 1 contains a summary of the technologies that are covered in the analysis.[3] We focus on technologies that are specific to automotive emissions control, and for which well-defined patent classes exist. For a more extensive discussion see, for instance, OECD (2004).

Table 1. **Automotive emission-control technologies covered**

1. Integrated technologies	
Air-fuel ratio devices	Mechanical control systems that inject fresh air into the exhaust manifolds of the engine in order to allow further combustion of exhaust gases (HC and CO), *e.g.* air injection reactors.
Oxygen, NO_X and temperature sensors	Provide feedback and increase competence of computerised control systems.
Fuel injection systems	Inject fuel continuously through nozzles at each intake port, the rate of injection being controlled by varying the pressure supplied to the nozzles by an electric fuel pump. Sequential fuel injection systems fire at the optimal time during engine rotation and thus allow for better air-fuel mixtures and therefore better performance and fewer emissions.
Exhaust gas recirculation (EGR) valves	Reduce NO_X emissions by re-introducing exhaust gases into the fuel mixture and lowering exhaust temperatures.
Electronic control systems and plasma-based technologies	Measure the air-fuel ratio in the exhaust and control the ratio of air to fuel in the combustion mixture, as well as provide control of other features such as spark timing, exhaust gas recirculation, idle speed, air injection systems, and purging of evaporative canisters (*e.g.* on-board diagnostic (OBD) systems).
Crankcase emissions control	Systems which include a crankcase vent port that requires closing the vent port and venting the crankcase emissions (the compressed gases that blow-by the piston rings in the crankcase mostly consisting of unburned or partly burned hydrocarbons) back into the air-intake system, instead of venting the blow-by gases into the atmosphere.
2. Post-combustion technologies	
Catalytic converters and regeneration	Devices placed in the exhaust systems capable of converting noxious emissions (CO, HCs and NO_X) into harmless substances (carbon dioxide, nitrogen and water vapour). A catalytic converter consists of a substrate providing a large surface area (a ceramic support with a wash-coat of (usually) aluminum-oxide) which is then layered with the catalyst (noble metals, like platinum, palladium, and rhodium, either singly or in combination). Catalysts increase the reaction rate between oxygen and emissions present in the exhaust, whose chemical reaction is otherwise too slow.

Patent counts

Patents and patent statistics have been widely used as indicators of inventive performance of a firm or an economy (Griliches,1990 and OECD, 2008). Patent data constitute a valuable source of information on the nature of the invention, containing discrete records which are categorised in specific technological fields.

The World Intellectual Property Organisation's (WIPO) International Patent Classification (IPC) system[4] is used to identify patent classes that match the automotive emission-control technologies as described above. The full list of IPC codes that deal with the purification of gases and emissions control in motor vehicles is given in the Appendix. These codes are broadly categorised into the two major technology groups identified above: 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.

Data on patent applications deposited at the European Patent Office (EPO) were extracted from the OECD Patent Database.[5] The data were then used to construct patent counts disaggregated by source country (country of origin of the inventor), priority year (the earliest year of application within a given patent family), and technology type. When interpreting the descriptive data it is important to bear the "home bias" in mind, with (for instance) German inventors much more likely to apply to the EPO than Japanese or US inventors.

Bearing this in mind, Figure 1 gives the aggregate patent counts for vehicle emission control technologies for the 15 countries with the highest counts over the period 1978-2004 (> 50 in total). Japan and Germany have the highest counts, followed by the United States. Canada has shown remarkable growth in recent years.

Figure 1. **EPO patent counts in automotive emissions control by country of inventor (1978-2004)**

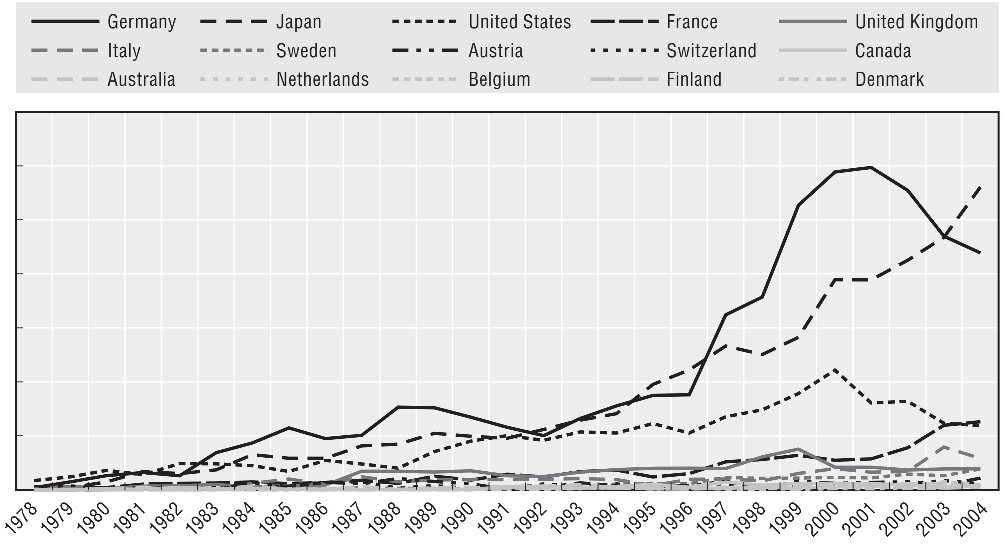
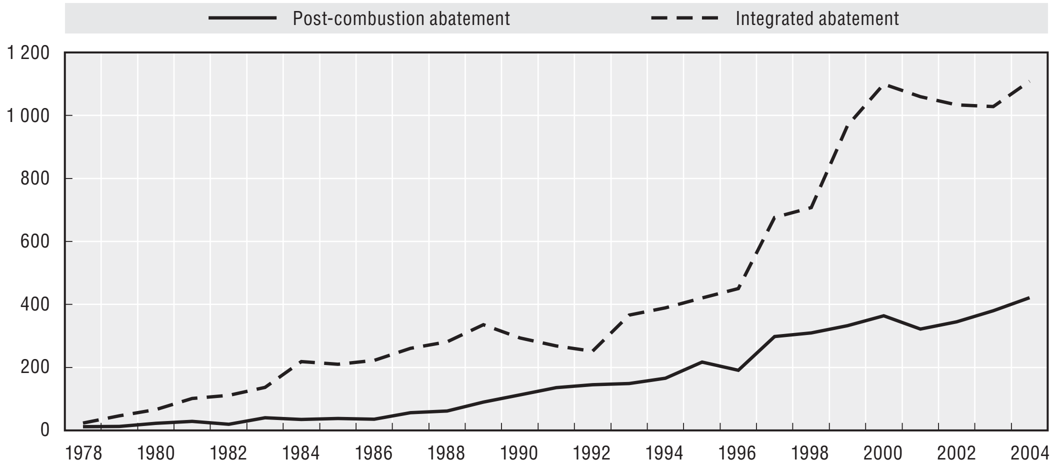


Figure 2 gives the same data by technology type, distinguishing between integrated emission-control technologies and post-combustion technologies (catalytic converters). Integrated technologies are more predominant, with the growth in recent years being very marked, increasing from approximately 400 per year in the mid-1990s to over 1 000 more recently. In recent years post-combustion technologies have represented 25%-30% of the total.

Figure 2. **EPO patent counts in automotive emissions control by type of technology (1978-2004)**



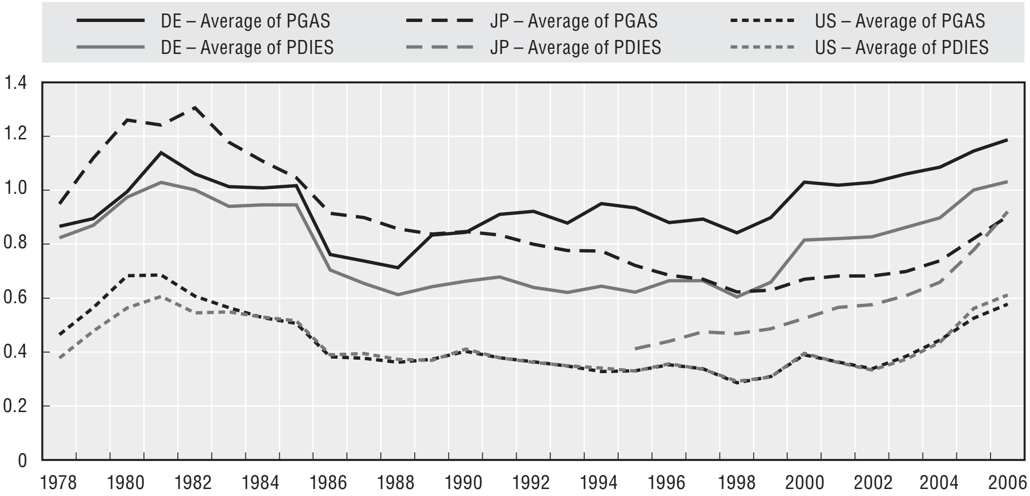
Factors determining patenting activity in automotive emissions control

A number of factors are likely to affect the rate and direction of innovation with respect to automotive emissions control, including general macroeconomic conditions (size and openness of an economy, integration in international trade) and general propensity to patent (strength of intellectual property rights regimes, scientific and research capacity). However, such factors affect patents in total and not specifically those associated with emission-control technologies.

Fuel prices

For the period 1978-2006, the most important development in international energy markets was the second oil supply shock in the late 1970s. Prices culminated at historic heights in 1981, then dropped somewhat after that point. Oil prices in recent years have been sufficiently high to consider present circumstances as representing a "third" oil shock. Figure 3 gives the post-tax price of gasoline and diesel in Germany, Japan and the United States.

Figure 3. **Post-tax price of gasoline and diesel (2000 USD per litre using PPP)**



Source: Own figure using data from IEA (2007).

Retail fuel prices have been substantially higher in Germany than in the US throughout the 1978-2006 period, with Japan in-between. Unlike in the United States where gasoline and diesel prices have been approximately equal during most of the period, in Germany and Japan gasoline has been the relatively more expensive fuel compared with diesel. This can affect the incentives for innovation in emission-control technologies. In general, rising fuel prices provide incentives for increased fuel efficiency. This can affect the rate of innovation with respect to emission-control technologies in general. More specifically, emission control technologies which result in both increased fuel efficiency and reduced emissions (*e.g.* on-board diagnostics) are likely to be relatively more attractive than other technologies (*e.g.* catalytic converters).

Environmental regulation in the automobile sector

There has been significant evolution in the key regulatory measures affecting the automobile sector. Given the tradability of vehicles and the relative importance of the US, Japanese and European markets we focus on regulations in these three regions. This section provides a brief overview of the relevant legislation. For a more extensive discussion of regulation and other strategies to reduce emissions from motor vehicles, see OECD (2004), Hascic (2006), and De Vries and Medhi (2008).

Emission standards

In response to environmental regulations introduced by a number of countries in the 1970s car manufacturers generally based their compliance strategies on the use of catalytic converters. In the early 1980s, some car manufacturers applied three-way catalyst in a closed-loop emissions control system using sophisticated electronic devices for controlling engine functions, while others relied solely on the use of three-way catalyst without these electronic devices (Bresnahan and Yao, 1985).

The standards applied in the United States have generally had a "technology-forcing" character, with the introduction of performance standards that cannot be met with existing technology and as such have not been demonstrated in practice (*e.g.* Gerard and Lave, 2005). "Technology-following" standards are less strict, and can be met with existing technology. It has been argued that European standards were primarily "technology-following" (Faiz *et al.,* 1996).

The United States established Tier I standards for HC and NO_x emissions in 1994, followed by Tier II standards in 2004.[6] Relative to the initial levels in the early 1970s, standards have become significantly more stringent. For example, compared with pre-regulation levels, the 2004 standards represent a reduction of 97% for HC, 94% for NO_x, and 95% for CO. Additional standards for particulate matter (PM) were implemented in 1994, and are currently set at 0.08 g/mile.[7]

Japan introduced the Air Pollution Control Law in 1968. Subsequent standards set in 1972 required a 90% reduction of CO and HC emissions by 1975 and a 90% reduction of NO_x emissions by 1976 (Zhu *et al.*, 2006, p. 8). Japanese automobile regulations are also embedded in the 1992 Motor Vehicle NO_x law, which specified performance standards for NO_x emissions from in-use vehicles. More recently, in joint cooperation with the Japan Automobile Manufacturers Association (JAMA) and the Petroleum Association of Japan (PAJ), the Japan Clean Air Program (JCAP) was established in 1996 with the aim to improve air quality. For diesel engines, the CO standard first coincided with the standard for gasoline engines in the period 1986-1999, and became more stringent in 2002.[8] The HC and NO_x standards for diesel have generally been less strict than the corresponding standards for gasoline engines.[9] Furthermore, PM standards for diesel came into effect after 1994 and gradually changed from 0.23 g/km to 0.0135 g/km in 2005 – about a 94% reduction.

In the European Union, the basis for union-wide standards for automobile emissions is laid down in Directive 70/220/EEC from 1970. The Directive specified the maximum limits for CO and HC vehicle emissions. In subsequent decades, the stringency levels have been increased through a series of amendments. For example, Directive 83/351/EEC imposed stricter CO standards and introduced limits on the combined HC + NO_x emissions; Directive 88/76/EEC provided additional restrictions on NO_x emissions separately; and Directive 89/441/EEC introduced standards for PM emissions. The most important amendments have been those termed Euro 1 – Euro 5. The 1992 Euro 1 performance standard required manufacturers to install three-way catalytic converters in gasoline vehicles. Since the 1996 Euro 2, there have been different standards for diesel and gasoline vehicles, both of which have become progressively stricter as they progress from Euro 2 to Euro 5.

Table 2 summarises the development of standards for Japan, the United States and the European Union for HC, CO and NO_x for petrol-driven vehicles. In sum, comparing the regulatory history of the three regions with respect to emission standards suggests that whereas the US and the EU regulations show a more gradual adjustment towards higher stringency levels, the Japanese standards were initially set at a relatively more stringent level and then remained more-less constant for a longer period of time.[10] The different temporal patterns of regulatory tightening, as well as the EU experience with joint standards for different pollutants (HC and NO_x), may have some implications for the nature of innovation.

Table 2. **Changes in performance standards for petrol-driven vehicles**[1]

	United States	Japan	European Union
1975	CO (15.0), HC (1.5) and NO_x (3.1)	CO (2.1) and HC (0.25)	CO (30.11) and HC (2.12)
1976	▼	NO_x (0.6)	
1977	NO_x (2.0)	▼	
1978		NO_x (0.25)	
1979	▼		
1980	CO (7.0) and HC (0.41)		
1981	CO (3.4) and NO_x (1.0)		
1982			
1983			▼
1984			CO (18.76) and HC + NO_x (5.43)
1985			
1986			
1987			
1988			▼
1989			CO (7.40) and HC + NO_x (1.97)
1990			
1991			▼
1992			CO (2.72) and HC + NO_x (0.97)
1993	▼		
1994	HC (0.25) and NO_x (0.4)		
1995			▼
1996			CO (2.2) and HC + N_x (0.5)
1997			
1998			
1999		▼	▼
2000		CO (0.67), HC (0.08) and NO_x (0.08)	HC (0.2) and NO_x (0.15)
2001			
2002			
2003			
2004			▼
2005	▼	▼	CO (1.0), HC (0.1) and NO_x (0.08)

1. US standards in grams per mile and Japanese and European standards in grams per kilometre. Note, however, that standards are not strictly comparable, depending upon characteristics of test cycles used for permitting.

Source: Hascic (2006).

On-board diagnostic systems

In addition to the use of emission standards, public policy has increasingly focused on the development and implementation of on-board diagnostic (OBD) systems. In general, two generations of OBD systems can be distinguished. The OBD-I system makes use of electronic means to diagnose engine problems and to control engine functions, such as fuel and ignition. Sensors are also used to measure the performance of the engine as well as the level of automotive emissions. In addition, the sensors are also helpful in providing early diagnostic assistance (B&B Electronics 2005). The OBD-II systems are more sophisticated and ensure that vehicles remain as "clean" as possible over their entire life by monitoring and automatically adjusting vehicle emission performance (USEPA 2004).

In the United States, the first implementation of OBD requirements occurred in California in 1988, and was implemented by the California Air Resources Board (CARB). This system (OBD-I) had to be installed beginning with all 1988 model-year vehicles. The requirements were particularly related to the control of fuel and ignition functions of the vehicle. Induced by this first generation of OBD systems in California, the 1990 Clean Air Act Amendments (CAAA) mandated the implementation of a more sophisticated and expanded OBD system for the United Staes as a whole. This advanced (OBD-II) system, developed by the Society of Automotive Engineers (SAE), became the basis for the legal standard set by the US Environmental Protection Agency (USEPA). The 1990 CAAA mandated that all light-duty vehicles and trucks built in 1996 and later are to be equipped with an OBD-II system.

In Japan, OBD requirements ran more-or-less in parallel with Japan's pursuit of a more stringent environmental policy with respect to exhaust emissions which were introduced in 2000. Since then, OBD requirements have also been explicitly mandated. However, Japanese car manufacturers already produced vehicles equipped with OBD-II systems since 1996, similar to the nation-wide implementation of OBD-II systems in the United States, perhaps in order to gain overseas market share, a point discussed below.

In the EU, Directive 98/69/EC mandated the introduction of OBD systems for emission control (Euro 3). Further OBD requirements were introduced in Directive 1999/96/EC which states that "From 1 October 2005, new types of vehicles, and from 1 October 2006, all types of vehicles, should be equipped with an OBD system or an On-Board Measurement (OBM) system to monitor in-service exhaust emissions".

In summary, the forerunner in the development and implementation of both OBD legislation and OBD systems was the United States, which introduced the first generation of OBD systems (OBD-I). At the federal level, the 1990 CAAA mandated the installation of the more advanced OBD-II system as of 1996. Although Japan formally mandated the implementation of OBD-II systems as of October 2000, Japanese automobile manufacturers had already installed this type of system since 1996. European legislation on OBD systems, included in Directive 1999/96/EC, lags behind the OBD policy implementation in both the United States and Japan. The first EU-wide installation of OBD systems was required by 2005.

Regulation tailored to OBD systems differs in nature from regulation that is explicitly directed towards reducing exhaust emissions. The "environmental" motivation for OBD regulation seems to have a more "technology-following" character. For example, the principal line of approach of OBD was on developing (general) improvements in engine performance and engine design, rather than on reducing emissions *per se*. The latter effects more-or-less came along with more advanced OBD systems. The policy implication of this is that the public motivation for OBD regulation came into being once these systems revealed their potential for environmental benefits, but only after they had already proven to be useful for "non-environmental" reasons (*i.e.* enhanced performance and diagnostics).

This makes the nature of OBD regulation different from regulation mandating the development and installation of catalytic converters. In the former case, there is a mix of private and social benefits, while in the latter case, the benefits are exclusively social. Whereas post-combustion devices only generate environmental benefits at the "end-of-pipe", the environmental benefits from OBD systems could be classified as being complementary with other benefits, such as increased fuel efficiency and reduced maintenance costs. As discussed in Labonne and Johnstone (2008), incentives for innovation in the two cases will be very different, with implications for policy design.

General market and policy conditions

Aside from public policy and fuel prices there are, of course, other important determinants of patenting activity for motor vehicle control technologies. Patent activity is clearly a result, in part, of national scientific capacity and general expenditures on research and development. In addition, the propensity of inventors from a particular country to patent is likely to change over time, both because different strategies may be adopted to capture the rents from innovation and because legal conditions may change through time. As such, in the empirical model presented below, a variable was included reflecting overall patent applications filed across the whole spectrum of technological areas. This variable thus serves as a "trend" and "scale" variable in that it controls for the changes in general propensity to patent over time and across countries.

Empirical model and results

An empirical model is developed in order to evaluate the effects of environmental policy and other factors on patenting activity in the area of motor vehicle emissions. The following reduced-form equation is specified:

$$ENVPAT_{i,t} = \beta_1 STD_{i,t} + \beta_2 OBD_{i,t} + \beta_3 GASPRICE_{i,t} + \beta_4 TOTPAT_{i,t} + \alpha_i + \varepsilon_{i,t} \qquad [1]$$

where *i* indexes country and *t* indexes year. The dependent variable is measured by the number of patent applications for integrated technologies (*PAT-INTG*) in one equation and for post-combustion technologies (*PAT-POST*) in a second equation.[11]

Explanatory variables include a vector of proxies for regulatory performance standards (*STD*), and for OBD (*OBD*) standards. Separate dummy variables are included for each of three regions. These are assumed to have an impact on patent activity in all countries since the market for motor vehicles is globalised and since these three regions represent a significant share of the global market. Regulatory developments in these three regions are likely to have an influence on inventors in all countries. However, differences in the "regional" impacts of regulations introduced in one jurisdiction are examined in the models estimated.

In addition, a variable reflecting domestic fuel prices was included. Since diesel and gasoline prices are so highly correlated within countries, only the variable for gasoline prices (*GASPRICE*) was used for the estimation. This varies across the whole panel. Various lag lengths were tested, and in the best-fitting models presented below a lag of three years is applied. Lags (and leads) were also tested for the regulatory measures but had no

Table 3. **Policy variables included in the model**

USOBD1	Dummy OBD regulation in United States (= 1 from 1988, = 0 otherwise)
USOBD2	Dummy OBD regulation in United States (= 1 from 1996, = 0 otherwise)
JPOBD	Dummy OBD regulation in Japan (= 1 from 2000; = 0 otherwise)
USSTD1	Dummy emission standards in United States (= 1 from 1981; = 0 otherwise)
USSTD2	Dummy emission standards in United States (= 1 from 1994; = 0 otherwise)
USSTD3	Dummy emission standards in United States (= 1 from 2003; = 0 otherwise)
JPSTD	Dummy emission standards in Japan (= 1 from 2000; = 0 otherwise)
EUSTD1	Dummy emission standards in Europe (= 1 from 1989; = 0 otherwise)
EUSTD2	Dummy emission standards in Europe (= 1from 1992; = 0 otherwise)
EUSTD3	Dummy emission standards in Europe (= 1 from 1996; = 0 otherwise)

appreciable effect on the results. This is certainly due in part to their rather crude construction as dummy variables. For a given regulation, a lag (or lead) of one year will only change the value of a single observation for a given country.

And finally, total patent applications for all technology fields that were filed at the European Patent Office (*TOTPAT*) are included to reflect differences in the propensity to patent in different countries, general scientific capacity, and framework conditions for innovation. The inclusion of a variable reflecting the value added in the transport sector was included, but due to the high number of missing observations for the sector in the OECD STAN database it was not included in the final models.

Fixed effects (α_i) are introduced to capture unobservable country-specific heterogeneity.[12] All the residual variation is captured by the error term ($\varepsilon_{i,t}$). A negative binomial model is used to estimate equation [1] (for details on count data models see, for example, Cameron and Trivedi, 1998; Maddala, 1990; Hausman, Hall and Griliches, 1984).

Empirical results for the two technology groups are presented below. Due to the high degree of correlation between some of the policy dummies, some of these were dropped. The results for integrated technologies (Table 4) indicate that fuel price (*GASPRICE*) has a positive and statistically significant (at the 1% level) effect on patenting activity. The results also suggest that higher patenting activity in general (*TOTPAT*) has a positive impact. However, the only regulations which have an effect on patent activity are the first OBD regulation (at the 5% level) and the Japanese OBD regulation (at the 1% level).

Table 4. **Results for integrated technologies (n = 525, 21 countries)**

	Coefficient	Standard error	P > |z|
GASPRICE	1.2109	0.2702	0.0000
USOBD1	0.3210	0.1554	0.0390
USOBD2	0.2160	0.1191	0.0700
JPOBD	0.2581	0.0965	0.0070
USSTD2	0.2586	0.1395	0.0640
USSTD3	0.0991	0.1022	0.3320
EUSTD1	0.3160	0.1728	0.0670
EUSTD2	0.1709	0.1284	0.1830
TOTPAT	0.0370	0.0105	0.0000

These effects may, of course, vary by region. As such, for those regulations which are statistically significant at the 5% level, variables are introduced which interact the regulations with regional dummies for Europe, North America and the Asia-Pacific region and likelihood-ratio tests are conducted to determine the statistical significance of the model relative to the restricted case in which the impacts are assumed to be equal across regions. The results are presented below, and indicate that the OBD1 regulations had a greater impact in Europe and Asia-Pacific than in North America itself. This may reflect the fact that the American car sector had anticipated (and perhaps influenced) the regulation prior to its introduction. The regulation came as more of a "shock" to foreign manufacturers. However, it should be noted that the regional interaction terms are not statistically different from one another. The Japanese OBD regulations (which came later) did not affect innovation in the North American market, but did have a positive and significant influence on innovation in the European and Asia-Pacific market.

Table 5. **Results for integrated technologies with regional interactions**

	Coefficient	Standard error	P > |z|
GASPRICE	0.8753	0.2625	0.0010
EU_USOBD1	0.8101	0.1035	0.0000
NA_USOBD1	0.4965	0.2014	0.0140
AP_USOBD1	0.7581	0.1983	0.0000
EU_JPOBD	0.6665	0.0838	0.0000
NA_JPOBD	–0.0843	0.1887	0.6550
AP_JPOBD	0.4436	0.1703	0.0090
TOTPAT	0.0758	0.0115	0.0000

Contrary to the above, the estimates given in Table 6 suggest that innovation for post-combustion technologies is primarily driven by environmental policy shocks. The coefficient for the price of gasoline is not significant. The coefficients of a number of regulatory standards (USSTD3, EUSTD1 and (almost) EUSTD2) are significant at the 5% level. The second US OBD regulation is also significant. Interestingly, in this case the variable TOTPAT is not significant, indicating that determinants of innovation for post-combustion technologies are distinct from the general determinants of innovation.

Table 6. **Estimation results for post-combustion technologies (n = 500, 20 countries)**

	Coefficient	Standard error	P>|z|
GASPRICE	–0.3367	0.3105	0.2780
USOBD1	0.3651	0.2036	0.0730
USOBD2	0.2925	0.1223	0.0170
JPOBD	0.1421	0.0992	0.1520
USSTD2	0.1875	0.1434	0.1910
USSTD3	0.3039	0.1067	0.0040
EUSTD1	0.6267	0.2132	0.0030
EUSTD2	0.2682	0.1377	0.0510
TOTPAT	0.0142	0.0116	0.2200

As with the previous case, region-specific interaction terms are introduced for those regulations which are significant at the 5% level. In this case the USOBD2 regulations affect innovation in Europe and Asia-Pacific, but not North America itself. The effects in the European and North American market are not statistically different. This may be for reasons similar to those hypothesised above concerning the effects of the

USOBD1 regulations on more integrated forms of innovation. The USSTD3 only affects innovation in post-combustion technologies in Asia-Pacific, while the EUSTD2 regulations affect innovation in both Europe and Asia-Pacific, but the regional interaction terms are not statistically different from one another. It is only the 1989 EU standards (EUSTD1) which impact all three regions. The differences in the coefficients between the three regions are statistically different from one another.

Table 7. **Results for post-combustion technologies with regional interactions**

	Coefficient	Standard error	P > |z|
GASPRICE	0.3101	0.3115	0.3200
EU_USOBD2	0.4420	0.0955	0.0000
NA_USOBD2	–0.2035	0.1645	0.2160
AP_USOBD2	0.3884	0.1480	0.0090
EU_USSTD3	0.1596	0.0990	0.1070
NA_USSTD3	–0.0329	0.1568	0.8340
AP_USSTD3	0.4485	0.1315	0.0010
EU_EUSTD1	0.9069	0.1439	0.0000
NA_EUSTD1	0.5828	0.2046	0.0040
AP_EUSTD1	1.6338	0.2381	0.0000
EU_EUSTD2	0.2743	0.1213	0.0240
NA_EUSTD2	0.3079	0.1875	0.1010
AP_EUSTD2	0.5826	0.1789	0.0010
TOTPAT	0.0479	0.0096	0.0000

Conclusions

Some innovations yield both private and public benefits (*e.g.* on-board diagnostics or fuel injection), while others yield only public benefits (*e.g.* catalytic converters). As such, one would expect to find that different factors are determinant in inducing innovation in the two cases. Drawing upon patent data, an analysis of patent activity in a cross-section of OECD countries for the period 1978-2005 was undertaken. On the one hand, it is clear that “foreign” regulations have a significant impact on domestic innovation. For a globalised industry such as the car market this is hardly surprising. However, the finding that foreign regulations can have a greater influence on domestic innovation than domestic regulations is, perhaps, surprising. This might be explained by the important role played by “home” manufacturers in the development of domestic regulations. Since such measures are anticipated (and perhaps influenced) by domestic manufacturers to a greater extent than foreign manufacturers, the introduction of the regulation is not as much of a policy “shock”, and its effect cannot be captured by a dummy variable of the kind used in this study.

On the other hand, in terms of the links between policy design and the nature of innovation induced, our results largely confirm our hypotheses. “Integrated” innovations which capture both private and public benefits are determined by gasoline prices and those policies which sought to encourage the use of technologies which yield both types of benefit. In addition, the general determinants of innovation in the economy (as proxied by total patent counts) are positively correlated with integrated innovations. Conversely, in the case of post-combustion technologies, it is primarily regulatory standards which drive innovation. Gasoline prices and the general rate of innovation have little influence. In effect, innovation efforts with respect to the attainment of environmental objectives are “hived off” from the influence of more general economic factors.

What does this mean for environmental policy? Firstly, the finding that environmental policies have an impact on innovation is hardly surprising. Whether through environmental taxes (as reflected in fuel prices) or standards, the shadow price of polluting (and not innovating in a manner which reduces pollution) will have risen. Clearly, while such innovation may reduce the costs of meeting given environmental objectives, this does not imply that such standards are socially optimal. Forcing excessive innovation through standards or taxes might actually reduce social welfare.

However, if it is possible to meet environmental objectives in a manner which allows (at least partly) for the realisation of private commercial objectives, the cost of environmental improvements is reduced. Whether or not firms are able to implement technologies which allow for this is dependent in part upon the regulatory framework. Prescriptive regulations which restrict the potential for manufacturers to exploit such synergies are likely to be more costly than would otherwise be the case. As such, the finding that innovation in integrated abatement technologies has been influenced by gasoline prices, general innovation capacity, as well as environmental regulations, is significant. In order to minimise the cost of the realisation of given environmental objectives it is important that regulations allow for innovation which can realise multiple (public and private) objectives. Whether or not "flexible" regulations are implemented will depend, of course, in large part upon the administrative costs of doing so. The widespread use of prescriptive standards is in part a reflection of the costs of monitoring emissions from mobile sources.

Notes

1. In the United States, Europe and Japan the contribution of road transport to CO emissions is 61%, 42% and 36%, respectively; the corresponding figures for NO_x emissions are 38%, 40% and 28% (OECD 2007).
2. In the United States, Europe and Japan the contribution of road transport to HC emissions is 25%, 20% and 6%, respectively; the corresponding figures for PM emissions in the United States and Europe are 3% and 17% (OECD 2007).
3. In general, abating pollution from vehicles must target both tailpipe as well as gas tank venting. While tailpipe emissions result from the combustion process, evaporative emissions can result even when the engine is idle. Technologies to control evaporative emissions require additional modifications, which are not necessarily related to engine design (*e.g.* capturing of vented vapours from within the vehicle, reducing refueling emissions). However, due to limitations in the patent classification system, this paper does not consider separately technologies which target evaporative emissions.
4. For further details on the latest, 8th edition, of the IPC see *www.wipo.int/classifications/ipc/ipc8*.
5. See *www.oecd.org/sti/ipr-statistics*.
6. Tier 2 for light-duty vehicles (cars and light trucks) was fully phased in by 2007. Heavy light-duty trucks will be fully phased in by 2009.
7. The NO_x standards for diesel engines are the same as the standards that apply to gasoline, with the exception of the period since 1994. From that time on, diesel standards are a bit more lenient (1.0 g/mile for diesel *versus* 0.4 g/mile for gasoline). As of 1994, PM standards for gasoline have been set at 0.08 g/mile.
8. The diesel standard was tightened from 2.1 g/km to 0.63 g/km, compared with 0.67 g/km for gasoline engines.
9. The exception is in 2005 when the HC standard for diesel became more strict (0.024 g/km for diesel *versus* 0.05 g/km for gasoline).
10. On the other hand, prior to reaching the standards that were in place as of 1975, Japan gradually set more stringent CO, HC and NO_x standards for gasoline vehicles in the period 1965-1975.

11. While it might be supposed that the European market can be treated as a single entity, correlations between the dependent variables (patent counts) and the principal explanatory variables (*e.g.* gasoline prices) are no higher within Europe than between European countries and North American or Asia-Pacific countries.
12. Including value added in the transport sector.

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APPENDIX I

List of Selected IPC Patent Classes Relevant for Automotive Emissions Control

Table A1. **Integrated technologies: Improved engine design or engine redesign**

Air-fuel ratio devices	
F01N 3/05	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust by means of air *e.g.* by mixing exhaust with air.
F02M 67/00+	Apparatus in which fuel-injection is effected by means of high-pressure gas, the gas carrying the fuel into working cylinders of the engine, *e.g.* air-injection type.
F02M 23/00+	Apparatus for adding secondary air to fuel-air mixture.
F02M 25/00+	Engine-pertinent apparatus for adding non-fuel substances or small quantities of secondary fuel to combustion-air, main fuel, or fuel-air mixture.
F02M 3/00-04	Idling devices
Oxygen, NO_x and temperature sensors	
F01N 11/00+	Monitoring or diagnostic devices for exhaust-gas treatment apparatus
F02D 41/14	Electrical control of supply of combustible mixture or its constituents (introducing closed-loop corrections).
Fuel injection systems	
F02M 39/00+	Arrangements of fuel-injection apparatus with respect to engines; Pump drives adapted top such arrangements
F02M 41/00+	Fuel-injection apparatus with two or more injectors fed from a common pressure-source sequentially by means of a distributor
F02M 43/00+	Fuel-injection apparatus operating simultaneously on two or more fuels or on a liquid fuel and another liquid, *e.g.* the other liquid being an anti-knock additive
F02M 45/00+	Fuel-injection apparatus characterised by having a cyclic delivery of specific time/pressure or time/quantity relationship
F02M 47/00+	Fuel-injection apparatus operated cyclically with fuel-injection valves actuated by fluid pressure
F02M 49/00+	Fuel-injection apparatus in which injection pumps are driven, or injectors are actuated, by the pressure in engine working cylinders, or by impact of engine working piston
F02M 53/00+	Fuel-injection apparatus characterised by having heating, cooling, or thermally-insulating means
F02M 55/00+	Fuel-injection apparatus characterised by their fuel conduits or their venting means
F02M 57/00+	Fuel injectors combined or associated with other devices
F02M 59/00+	Pumps specially adapted for fuel-injection and not provided for in groups F02M 39/00 to F02M 57/00
F02M 61/00+	Fuel injection not provided for in groups F02M 39/00 to F02M 57/00
F02M 69/00+	Low-pressure fuel-injection apparatus
F02M 71/00+	Combinations of carburettors and low-pressure fuel-injection apparatus
Exhaust Gas Recirculation (EGR) valves	
F01N 5/00+	Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy

Table A1. **Integrated technologies: Improved engine design or engine redesign** *(cont.)*

	Electronic control systems and plasma-based technologies
F02D 41/00+	Electrical control of combustion engines; Electrical control of supply of combustible mixture or its constituents
F02D 43/00+	Conjoint electrical control of two or more functions, *e.g.* ignition, fuel-air mixture, recirculation, supercharging, exhaust-gas treatment
F02D 45/00+	Electrical control not provided for in groups F02D 41/00 to F02D 43/00
F02M 51/00+	Fuel injection apparatus characterised by being operated electrically
F01N 9/00+	Electrical control of exhaust gas treating apparatus
	Crankcase emissions and control
F01M 13/04	Crankcase ventilating or breathing: having means of purifying air before leaving crankcase, *e.g.* removing oil

Table A2. **Post-combustion devices**

	Catalytic converters, lean NO_x catalysts, NO_x absorbers, catalytic regeneration technology
F01N 3/08-34	Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust; for rendering innocuous by thermal or catalytic conversion of noxious components of exhaust
B01D 53/92-96	Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of engine exhaust gases; Regeneration, reactivation or recycling of reactants.
B01J 23/40-46	Catalysts comprising metals or metal oxides or hydroxides; of the platinum group metals