

Innovation, the diesel engine and vehicle markets: Evidence from OECD engine patents



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ABSTRACT

This paper uses a patent data set to identify factors fostering innovation of diesel engines between 1974 and 2010 in the OECD region. The propensity of engine producers to innovate grew by 1.9 standard deviations after the expansion of the car market, by 0.7 standard deviations following a shift in the EU fuel economy standard, and by 0.23 standard deviations. The propensity to develop emissions control techniques was positively influenced by pollution control laws introduced in Japan, in the US, and in the EU, but not with the expansion of the car market. Furthermore, a decline in loan rates stimulated the propensity to develop emissions control techniques, which were simultaneously crowded out by increases in publicly-funded transport research and development. Innovation activities in engine efficiency are explained by market size, loan rates and by (Organisation for Economic Cooperation and Development) diesel prices, inclusive of taxes. Price effects on innovation, outweigh that of the US corporate average fuel economy standards. Innovation is also positively influenced by past transport research and development.

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1. Introduction

The paper identifies the historical factors that influence firm innovation of diesel engines, with a focus on the EU, Japan and US markets in 1974–2010. Despite vast research on innovation, the relationships among environmental policy, publicly-funded transport research and development (R&D) investment and patents, are not well known. Diesel engine innovation is closely linked to the car, truck and bus markets in Japan, the US, the EU and China.¹ A major benefit of rapid innovation is that the costs of climate policy for the transport sector can be lower than costs in the absence of innovation. Innovation can turn public RD, for energy efficient engines, into a cost effective investment.

2. Background

An innovation is defined by Freeman and Soete (1997) as the means of matching technical options to market opportunities through activities including experimental development and design, trial production and marketing. An innovation can be

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¹ Amongst OECD countries, the fraction of diesel fuel in transport fuels, excluding rail and water, was 14% in 1973 rising to 34% in 2010 (International Energy Agency, 2010) and growing at nearly four times the rate of gasoline consumption. In China, diesel accounts for 60% of fuel used in transport.

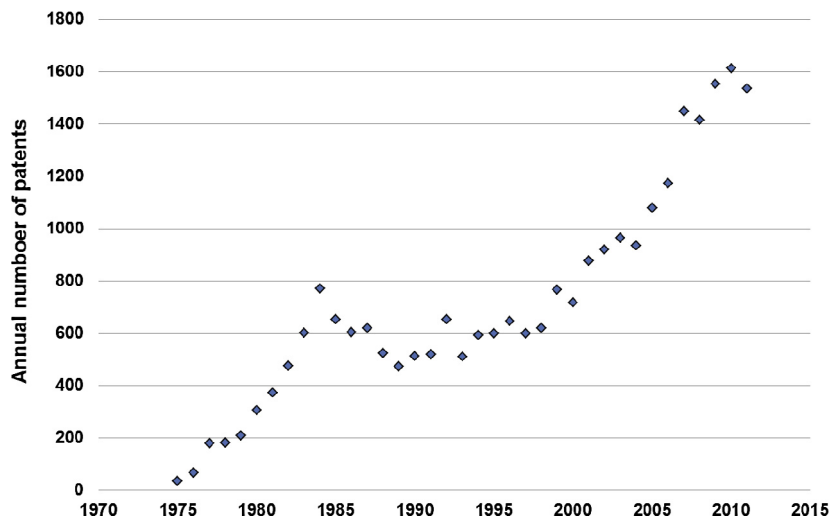


Fig. 1. Diesel engine patent counts: US, Japan, EU and rest of the world. Note: Annual number of patents by date of publication. Source: [European Patent Office \(2012\)](#).

either product or process related. In the transport context, because diesel engine technology is associated with poor air quality and with non- CO_2 emissions, improvements in pollution technology have been sought. The [European Commission \(EC\) \(2008\)](#) introduced the Air Quality Directive. In addition, diesel engines emit considerable amounts of CO_2 ([Bonilla, 2009](#)), resulting in continued efforts to improve fuel efficiency. [Fig. 1](#) uses patent data to show technological changes of the diesel engine between 1974 and 2010.

Despite the continued rise in patent registrations (setting aside the hybrid diesel) there have been no radical innovations in vehicle engines for 50 years. There have been waves of incremental innovations and we focus on these in the context of environmental laws, air pollution standards and engine efficiency standards, based on the premise that these act as incentives for firms to find new, and cheaper, methods of reducing pollution ([Porter, 1991](#)). Our patent dataset covers these main diesel engine categories and considers diesel engine design and air pollution control innovation in Japan, US, and the EU.

We examined 26,378 patents registered between 1974 and 2010, most of which originate from independent inventors, car firms and components firms based in Japan, the EU and the US.² Independent variables include measures of energy prices, three measures of market size, one metric of public R&D expenditure, three metrics of NOx emissions limits, and two of vehicle fuel efficiency standards. The year of vehicle sales is lagged by two periods over 1978–2008. Three models are used. One tests whether the propensity to innovate responds to oil prices, to public R&D expenditure, to standards of diesel engine efficiency, and more crucially to market size factors. The second tests if the propensity to innovate increases after the introduction of air quality laws in key Organisation for Economic Cooperation and Development (OECD) countries. The third considers factors explaining the growth of innovation in diesel engine efficiency.

Non- CO_2 pollution standards are temporally correlated to both growth in patents and to the number of patent categories ([Fig. 2](#)). Policy also has had a role. Besides the EC standard of 2008, non- CO_2 pollution standards were introduced in the 1980s and 1990s, by the US, Japan, and the EU, with the latter being the least strict in part because it has a large diesel car stock. The timing of pollution standards was vital to raise the level of innovation of the diesel engine. These pollution standards are also linked to innovations that control exhaust gas emissions, mainly NOx.³

Our analysis has its foundation in a number of prior studies, including those by the [Organisation for Economic Cooperation and Development \(2011\)](#), of patents between 1965 and 2009. This analysis found that fuel taxes play the largest role in diesel engine innovation, but omitted the effects of public and private R&D funding. The [US Environmental Protection Agency \(2013\)](#) reports that many innovations in fuel injection and variable valve timing are major factors in fuel efficiency; fuel injection systems having replaced carburetors 20 years previously. These technologies are now being replaced by the direct injection system, particularly, in gasoline engines. Many studies find evidence that actions by public policy makers on non- CO_2 and on CO_2 emissions controls raise the innovation effort of firms ([Organisation for Economic Cooperation and Development, 2011](#); [Hascic et al., 2009](#)).

Difficulties arise with these and similar studies in that they rely on aggregate data on energy-related innovations, and that they make no distinction between national markets i.e. car sales, cost of capital, or the effects of public R&D. We adopt a more disaggregate approach.

² The data are grouped by 'diesel engine' categories and include innovations in diesel engine design, air pollution control.

³ Japan's NOx standard was introduced in 1974; the US NOx limits set in 1976; and the Euro NOx limit for diesel in 2000 ([Hascic et al., 2009](#)). The first US non- CO_2 standards, set in 1980, covered HC and the NOx diesel emissions and led to significant increases in innovations. The US Clean Air Act of 1990 also led to rapid innovation in pollution control. A series of pollution controls introduced in the EU (Euro III) had a similar effect ([Lutsey, 2012](#)).

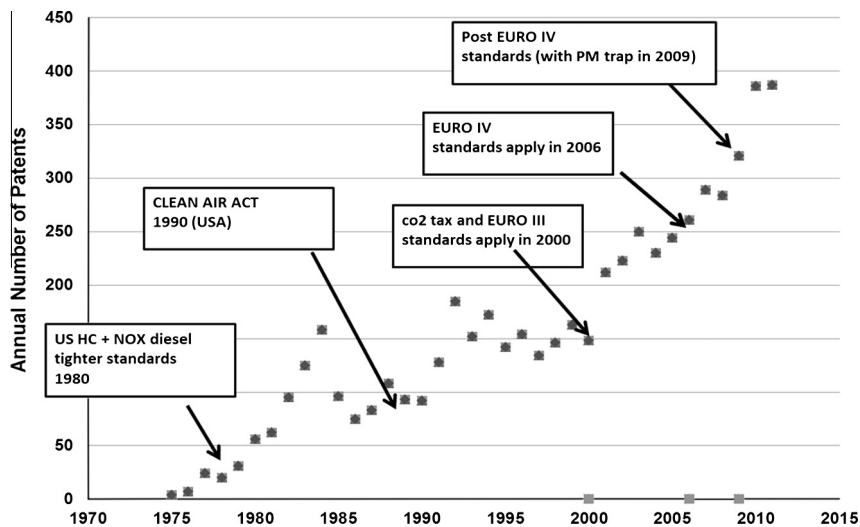


Fig. 2. Pollution control innovations for 'diesel and exhaust gas' engines. Note: counts by year of publication. Source: European Patent Office (2012).

There is some evidence that pollution standards have affected the level of innovation of the diesel engine, although proving causality is difficult. The legislation may, for example, have simply coincided, for political reasons, with innovations that were reaching the market already.

3. Approach

Our focus is not on radical innovation but on incrementalism – innovation that does not result in breaks with past technological patterns. The types of innovations that we considered is based on Organisation for Economic Cooperation and Development (2009):

- air to fuel ratio,
- electronic fuel injection,
- engine management systems, on-board diagnostics, and sensors,
- ignition timing, variable valve timing, variable compression ratio, combustion chamber geometry,
- engine performance during cold start acceleration,
- combustion, air and fuel conditioning.

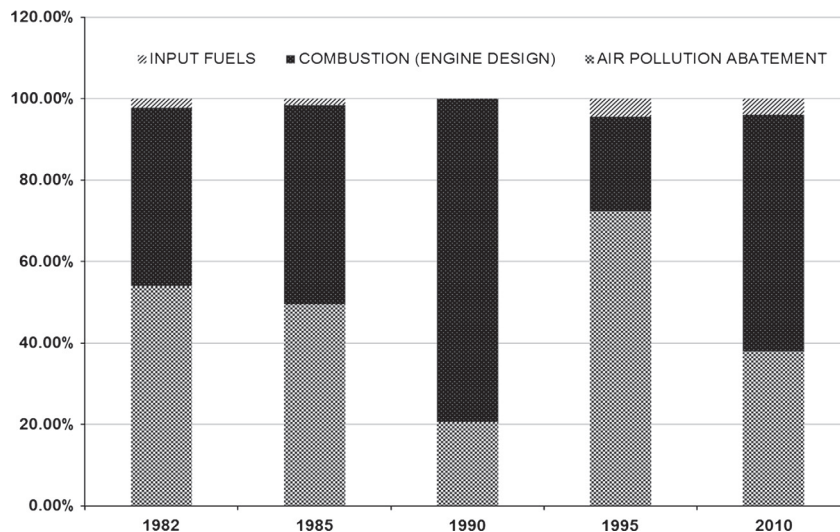


Fig. 3. Innovations for diesel vehicle engines. Source: European Patent Office (2012).

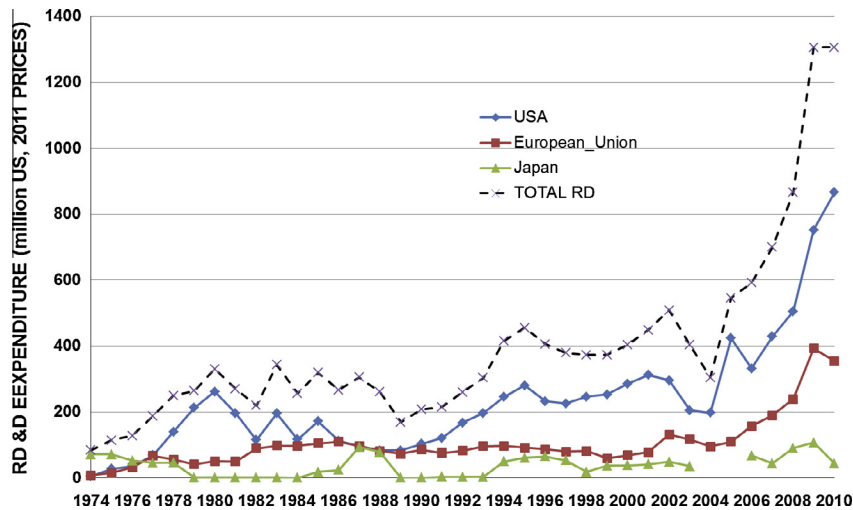


Fig. 4. Public funding for R&D in transport between 1974 and 2010 for the OECD countries. *Note:* Data are in \$million in constant 2011 prices and exchange rates. The EU in this context includes 21 nations. Transport RD is classified by the [International Energy Agency \(2011a\)](#) as including categories of RD for 'on road vehicles', 'vehicle batteries', 'advanced power electronics', 'motors', 'advanced combustion engines', 'electric vehicle infrastructure', 'fuel for on-road vehicles', 'material for on road vehicles', 'unallocated transport', 'off road transport and transport systems', as well as other transport. The IEA does not report a breakdown for RD investment of these classifications for all years but the 'on road vehicles' is the main item in 2010. *Source:* [International Energy Agency \(2012\)](#).

Data on patents is taken from the [European Patent Office \(2012\)](#) that is accessed through ESPACE. This contains data from more than 90 countries. Our search strategy used international patent (IPC) codes to identify keywords and returned three categories of innovations as well as subfields ([Fig. 3](#)). The patents are sorted by year of publication to ensure that only successful ones are included. [Fig. 3](#) also compares innovations by category between 1982 and 2010. The share of combustion patents, mostly involving engine efficiency, increases between 1982 and 1990, coinciding with two peaks of public R&D funding: 1980 and 1985 ([Figs. 2 and 4](#)). Engine efficiency innovations peak in 1990, and by 2010 they are largest contributor to engine innovation. Engine efficiency performance is negatively correlated to the adoption of the catalytic convertor and the introduction of tighter exhaust gas regulations ([OECD, 2009](#)).⁴ [Fig. 3](#) also shows that the share of pollution abatement patents fell between 1995 and 2010, while that of input fuels patents is small. The main source of innovation (within the combustion item, [Fig. 3](#)) was engine efficiency rather than improvements in pollution control between 1990 and 2010.

[Fig. 4](#) shows the volatility of publicly-funded transport R&D between 1974 and 2010. The effect of transport R&D funding on innovation generally involves time lags that increase the uncertainty of patenting activity.

The transport R&D measure includes labour and capital expenditures, but excludes some scientific and technical activities. Transport R&D growth matches that of engine efficiency patents in the last decade ([Fig. 4](#)) and shows that 97% of publicly financed transport R&D takes place in a small number of countries. The subcategory of 'on-road vehicles' within the 'transport R&D' category is the largest fraction. The R&D data has two disadvantages: first, disaggregated data for transport R&D categories are only available for 2009–2010; and secondly, the R&D statistics in [Fig. 4](#) exclude private funding which is important in Japan and the EU.

After the US, the key countries in transport R&D funding are Japan and Germany with South Korea and China becoming increasingly important (not shown in [Fig. 4](#)). For private firms, the incentive to innovate can stem from the need to compete in new product markets or from the need to reduce the effect of high energy prices. Historically, the US has shown the largest public R&D funding, but this has been volatile with peaks in 1990, 1995, 2005, and 2010–2011. These peaks correlate with high oil prices.⁵ The increase in US public R&D funding in recent years may also be due to the introduction of the American Recovery and Reinvestment Act in 2009 ([Yergin, 2010](#)).

[Fig. 5](#) provides patent counts for 1974–2010 against diesel vehicle sales in the EU. The data series move in tandem because innovators will be influenced by the expected market size; Europe is the largest diesel private car market in the world. The data are based on the published patents 18 months after they are filed. Thus, microeconomic events that occur prior to a patent application can influence decisions to innovate. It takes 4 years for an inventor to be granted a patent.

[Popp \(2002\)](#), [Hascic et al. \(2009\)](#), [Crabb and Johnson \(2007\)](#) and others have found expected oil prices to be a primary motivator of innovations. Oil prices were relatively stable in the 1980s and 1990s but by the early 2000s, had quintupled with engine efficiency patents growing simultaneously.

⁴ Diesel engines have higher non-CO₂ emissions than gasoline engines, however, the latter are less fuel efficient.

⁵ Transport R&D funding accounts for 17% of the R&D energy budget for the US; 1% for Japan and 6% for the EU in 2010 ([International Energy Agency, 2012](#)).

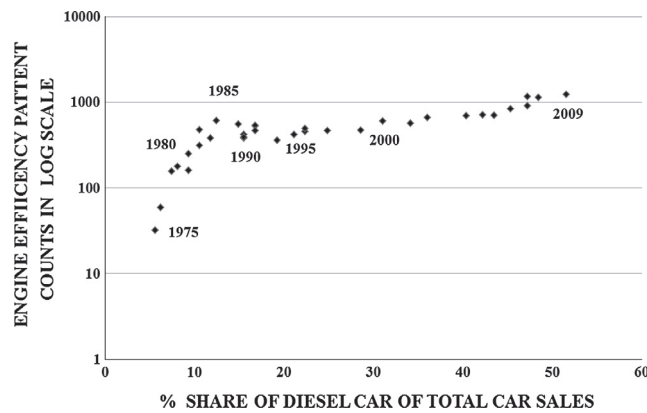


Fig. 5. Annual patent activity and the share of diesel car sales lagged 1 year for European Union data. Source: European Patent Office (2012), Joint Research Center (2003) and Eurostat (2012).

Table 1

Summary of data used, 1974–2010. Sources: Diesel and engine design patents (European Patent Office, 2012); diesel and oil prices (International Energy Agency, 2011b); EU Voluntary Agreement (Organisation for Economic Cooperation and Development, 2009); RD funding in transport (International Energy Agency, 2012); loan rate Japan (Bank of Japan, 2012); US loan rate (US Federal Reserve, 2012); trucks and buses sales in Japan (Japan Automobile Manufacturers Association, 2012; IEEJ, 2010); sales of US trucks (Davies and Diegel, 2012); EU sales of diesel cars (Joint Research Center, 2003; Eurostat, 2012); CAFE data (US Department of Transportation, 2012); NOx data (OECD, 2009).

Variable name and units	Median	St. dev.	Maximum
Diesel patents (US, Japan and EU)	693	421	1612
Patents: engine design (fraction of diesel engine patents; US, Japan and EU)	0.79	0.05	0.89
Patents counts: pollution control (fraction of diesel engine patents; US, Japan and EU)	0.20	0.05	0.30
Diesel prices (\$/litre using purchasing power parity). With tax included)	0.94	0.41	1.90
OECD average oil price (\$ 2011 prices)	33	22	97
NOx standard (parts/million) (Japan)	113	172	450
Japan discount (loan) rate (Bank of Japan) (%)	3.34	2.70	9.00
US Treasury bill rate (secondary market discount basis) (%)	5.62	2.99	13.16
EU Voluntary Agreement on fuel efficiency (dummy variable)	0.40	0.49	1.00
CAFE (miles/gallon)	20.67	1.42	24.20
Public R&D funding Transport (millions US, 2011 const. prices)	313	239	1135
Sales of Japanese trucks and buses (000s)	1988	596	3004
Sales of US trucks and vans (000s)	5810	2414	9793
Sales of diesel vehicle in EU (% share)	23	14	51

4. Method

Table 1 lists the input data used in our econometric analysis. Between 1974 and 2010, patenting activity, mostly in Japan, the EU and the US, averaged 693 patents a year. On average, engine efficiency innovations accounted for 79% of all diesel patents at a time when oil prices were \$33 a barrel (average diesel of \$0.94 a litre); and an average of two million trucks were sold in Japan and 5.8 million in the US. On average, 23% of passenger car sales in Europe were diesel based in this period.

Our first two models represent the propensity of firms to innovate in terms of engine efficiency and pollution control technologies, while the third estimates factors influencing the growth of car firms' innovative activity in engine efficiency between 1984 and 2010. The data were ordered using Excel's pivot option to visualise the entire set of patent information. Patent data was obtained for each IPC (international patent classification) of patent, and the company owning the patent.⁶ All three models mainly focus on innovations by private firms. Eq. (1) summarises the hypothesised relation between innovation, public R&D, fuel economy standards, market size, diesel price and loan rates, for 1974–2008. We expect positive coefficients (β) except for the *LoanR* variable. The model used is:

$$\begin{aligned} \text{epat}_t / \text{totdiesel}_t = & \alpha + \beta_1 (\text{PUB R\&D}_{t-1}) + \beta_2 (\text{oilpOECD}_t) + \beta_3 (\text{EUSales}_t) + \beta_4 (\text{JPSales}_t) + \beta_5 (\text{EUVA}_{t-1}) + \beta_6 (\text{LoanR}_t) \\ & + \beta_7 (\text{time trend}) + \varepsilon_t \end{aligned} \quad (1)$$

⁶ The ESPACE database (European Patent Office, 2012) provides IPC codes used to order the data for pollution control innovations and engine design.

where $epat$ is used to calculate the annual percentage of successful diesel engine efficiency patents of total diesel engine ones ($totdiesel$); $R\&D$ is funding in transport R&D in the OECD; $oilpOECD$ is oil prices in the OECD; $EUSales$ is the ratio of diesel car sales to total car sales; $JPSales$ is sales of trucks and buses in Japan; $EUVA$ is European Union Voluntary Agreement for fuel efficiency (1 for 1995–2008; 0 otherwise); $LoanR$ is the loan rate in Japan; t is a continuous time tend; and ε is the error term. Annual data is used throughout. The coefficients are expected to be positive except for the cost of capital in the US ($FedUS$).

Eq. (2) is used to estimate the propensity to innovate in pollution control techniques from 1984 to 2008:

$$\begin{aligned} envpat_t/totdiesel_t = & \alpha + \beta_1(PUB\ R\&D_t) + \beta_2(diep\ OECD_t) + \beta_3(StaNoxJP_t) + \beta_4(StaNoxUS_t) + \beta_5(EuroNox_t) \\ & + \beta_6(EUVA_{t-1}) + \beta_7(EUSales_{t-1}) + \beta_8(FedUS_t) + \beta_9timetrend + \varepsilon_t \end{aligned} \quad (2)$$

where $envpat$ is used to produce the percentage of successful patents for pollution abatement; $totdiesel$ is defined in Eq. (1); $R\&D$ is research and development funding in transport in the OECD; $diepOECD$ is diesel prices in the OECD; $StaNoxJP$ is the Japanese emissions standard; $StaNoxUS$, is the US NOx emissions standard; $EuroNOx$ is the EU emissions standard; $EUVA$ and $EUSales$ are as in Eq. (1); $FedUS$ is the US Treasury bill rate; t , is a continuous time variable covering 1984–2008. Annual data is used throughout.

Eq. (3) tests the factors of growth of innovations of diesel engines. It is constructed in accordance with the linear and quadratic explanatory variables detailed in Table 4. This model introduces a lag operator ($R\&D$) $_{t-k}$ which is varied between 2 and 4 years ($0 < k \leq 4$). The dependent variable is measured in the annual number of patents (Table 1). $t = 1984$ –2010 years.

$$\begin{aligned} epat = & \alpha + \beta_1(PUB\ R\&D_t) + \beta_2(PUB\ R\&D_{t-2}) + \beta_3(PUB\ R\&D_{t-3}) + \beta_4(PUB\ R\&D_{t-4}) + \beta_5(PUB\ R\&D_{t-3}^2) \\ & + \beta_6(PUB\ R\&D_{t-4}^2) + \beta_7(diep\ OECD_t) + \beta_8(EUSales_t) + \beta_9(USCAFE_t) + \beta_{10}(LoanR_t) + \beta_{11}(timetrend) + \varepsilon_t \end{aligned} \quad (3)$$

5. Results: factors for engine efficiency and air pollution innovation

Results are shown in Tables 2–4. Eq. (1) (Table 2) can be interpreted as the propensity of firms to innovate in diesel engine efficiency. This can be explained by market size (diesel cars in the EU and trucks in Japan), the effect of the fuel economy standards (EU Voluntary Agreement of 1995), and by a time trend. This suggests that the EU Agreement impacts engine efficiency innovation by giving incentives to develop better technologies (i.e. direct engine injection) that can lower costs of energy efficiency measures. This reduces CO₂ emissions and abatement costs. The effects of public R&D and oil prices (Table 2) do not help explain the change in the propensity of firms to develop diesel engine efficiency, although Eq. (1) only includes the effect of public R&D finance on innovation.

Table 2 shows that the propensity of firms to innovate in diesel engine efficiency is partly and positively correlated with a 'home market size effect'. This applies to Japan and the EU, but not to the US, possibly because Japanese firms are innovating for the EU diesel car market as well as for their own. The positive coefficient, of truck sales confirms that expected markets are important in influencing whether a R&D programme should receive funding. The propensity of firms to innovate in efficient diesel engines is weakly linked to lower loan rates in Japan; the coefficient is not statistically significant.

A firm's propensity for innovation in pollution control is reduced by the effects of EU diesel car sales and public R&D (Table 3). The effect of car market size on innovation is not positive because pollution control innovations preceded the development of the vehicle market. The impact of public R&D funding crowds-out pollution control innovations. The effect of diesel prices, inclusive of taxes, is non-positive. High prices discourage vehicle buyers, and in turn, this reduces the demand for innovation of pollution controls. This result confirms that diesel price, and a growing truck and car market, are weak tools since they have no effect on the propensity for innovation in pollution control technologies (Table 3). They relate to non-energy saving innovations.

Table 3 shows that pollution control innovations in Japan and the US responded positively to the introduction of NOx emissions standards, although the effect of the Euro-NOx emissions standard is weaker. The NOx standards have a consistently positive impact on innovation. The effect of the EU Voluntary Agreement on pollution control innovation also shows the correct sign since there is usually a trade-off between improving fuel economy (engine design) and pollution control technologies. Firms' propensity for pollution control innovation is also associated with the availability of finance reflected by the loan rate coefficient (Table 3).

Table 4 shows the results of the factors which influence the growth of innovations of diesel engines. The non-linear terms describe the effects of public R&D. Engine innovation responds to three factors: public R&D (with several lags), market size (EU car markets), and to diesel price (including taxes). Government actions (US CAFE and taxes on diesel in the EU) do enhance innovation and so does the ability to finance innovation. Introducing the non-linear terms gives a positive association between public R&D and innovation. The remaining explanatory variables are statistically significant.

6. Innovation intensity

The ratio of patents for diesel engine per \$thousand of public R&D expenditure has been highly volatile. After growing between 1975 and 1990 (Fig. 6), it fell in the early 1990s, and recovered in 2005. This trend indicates that the multiplier effect of public R&D expenditure is increasing. It also indicates that it is becoming easier over time to innovate in engine technol-

Table 2

Results: Propensity for diesel engine efficiency innovation, 1974–2008.

<i>Independent variable</i>	
Public R&D (transport) (1 year lag)	0.10 [*]
Oil price	0.001
EU ratio: diesel cars to car sales (1 year lag)	1.98 ^{***}
Japanese sales of trucks and buses	0.60 ^{***}
Loan rate (Japan)	−0.23
EU voluntary fuel efficiency agreement (1 year lag)	0.70 ^{***}
Time trend	2.77 ^{***}

R^2 : 0.70; DW: 1.39. Coefficients represent the standard deviation change in the dependent variable after one standard deviation shift in the independent one.

^{*} Statistical significance at less than 10%.

^{**} Statistical significance at less than 5%.

^{***} Statistical significance at less than 1%.

Table 3

Results: Propensity for emissions control innovation, 1984–2010.

<i>Independent variable</i>	
Public R&D (transport)	−0.70 ^{***}
Diesel price (tax inclusive, OECD average)	−0.52 [*]
Japan's Sta. – NOx emissions (parts/million)	0.252 [*]
US Sta. – NOx-HC standards (kg/km)	0.44
EURO NOx	0.176
EU Voluntary Agreement	−0.542 [*]
EU ratio diesel to car sales (2 year lag)	−1.71 ^{**}
US Treasury bill rate (secondary market discount)	−0.58 ^{***}
Time trend	3.3 ^{***}

R^2 : 0.724; DW: 1.95.

^{*} Statistical significance at less than 10%.

^{**} Statistical significance at less than 5%.

^{***} Statistical significance at less than 1%.

Table 4

Results: Growth of engine efficiency innovation; 1984–2010.

<i>Independent variable</i>	
Public R&D	0.44 ^{***}
R&D (2 year lag)	0.2 [*]
R&D (3 year lag)	0.67 ^{**}
R&D (4 year lag)	0.52 ^{**}
R&D 3 year lag (quadratic term)	−0.89 ^{***}
R&D 4 year lag (quadratic term)	−0.53 ^{**}
Diesel prices (tax inclusive, OECD average)	0.26 ^{***}
EU sales: diesel vehicle (ratio of vehicle sales)	0.68 ^{***}
US café (mpg)	0.17 [*]
Loan rate (Japan)	0.31 ^{**}
Time trend	−0.32 ^{**}

R^2 : 0.98; DW: 2.39.

^{*} Statistical significance at less than 10%.

^{**} Statistical significance at less than 5%.

^{***} Statistical significance at less than 1%.

ogies. Two points can be drawn from Fig. 6. First, that the productivity of public R&D improved but only slowly in the last two decades. Secondly, that the point at which returns to investment in public R&D diminish has not been reached, thus further increases in public R&D are worthwhile.

7. Conclusions

Our time-series model uses a large scale patent dataset. It shows that the propensity of firms to be innovative in diesel engine efficiency is explained by: loan rates, fuel economy standards, and the expanding car and truck markets of key countries. A firm's propensity to improve pollution control techniques, however, is crowded-out by transport R&D funding. The introduction of air pollution standards is associated with increases in pollution control innovations. The EU Voluntary

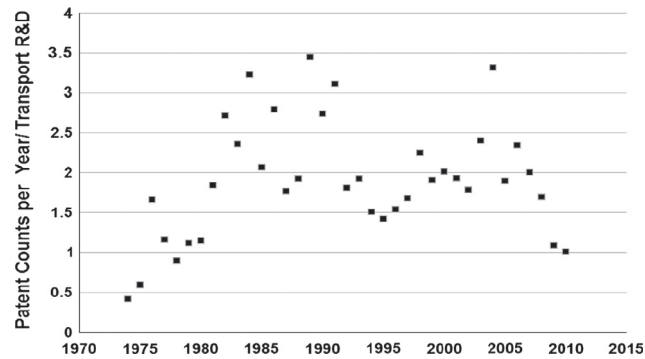


Fig. 6. Innovation intensity (patents per public funding R&D in transport in \$millions at 2011 prices. Source: Based on International Energy Agency (2012), European Patent Office (2012).

Agreement does not spur pollution control innovation because of trade-offs between improving fuel economy and pollution control technologies. Equally, diesel prices and car market size do not accelerate this type of innovation, while access to cheap finance does support pollution control innovation.

The analysis of the factors that explain the growth of innovation by firms in engine efficiency shows a positive non-linear effect of transport R&D, but the effect of this type of R&D is less influential. The role of private R&D funding is likely to be as important; our model provides evidence regarding the role of public R&D funding. This category of innovation activity is dominated by private firms that are conscious of market size factors. The evidence confirms that engine efficiency innovation is induced by fuel prices and the CAFE limits.

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References

- Bank of Japan Statistics, 2012. The Basic Discount Rate 1973–2012. <<http://www.boj.or.jp/en/statistics/boj/other/discount/index.htm/>> (downloaded 20.12.12).
- Bonilla, D., 2009. Fuel demand on UK roads and dieselisation of fuel economy. *Energy Policy* 37, 3769–3778.
- Crabb, J.M., Johnson, D.K.N., 2007. Fuelling the Innovative Process: Oil Prices and Induced Innovations in Automotive Energy Efficient Technology. Working Paper. Colorado College, College of Business and Economics.
- Eurostat, 2012. Eurostat Statistics. <<http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/>>.
- European Commission, 2008. EC Directive of the European Parliament and of the Council of the 21 May, 2008 on Ambient Air Quality. <<http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF>>.
- European Patent Office, 2012. ESPACE. <<http://espace.net.com>> (January 2012).
- Davies, S.C., Diegel, S., 2012. Transportation Energy Data Book, 30th ed. Oak Ridge National Laboratory, Center for Transportation Analysis, Oakridge.
- Freeman, C., Soete, L., 1997. The Economics of Industrial Innovation. Routledge, Abingdon.
- Hascic, I., De Vries, F., Johnstone, N., Neelakshi, M., 2009. Effects of environmental policy on the type of innovation: the case of automotive emissions control technologies. *OECD J.: Econ. Stud.* 22, 49–66.
- International Energy Agency, (2010) Statistics: Oil information. Paris, pp. 1–746. (various years).
- International Energy Agency, 2011a. IEA Guide to Reporting RD&D Budget expenditure statistics. IEA, Paris.
- International Energy Agency, 2011b. Energy Prices and Taxes. Paris (various issues).
- International Energy Agency, 2012. Statistics Energy R&D, Database. 2012.
- Institute of Energy Economics, 2010. Energy Data and Modelling Center. The Energy Conservation Centre, Tokyo.
- Japan Automobile Manufacturers Association, 2012. The Motor Industry of Japan. Report, Tokyo. <www.jama-english.jp>.
- Joint Research Center, 2003. Dynamics of the Introduction of New Passenger Car Technologies. The IPTS Transport Technology Model. Report by Christidis, P., Hidalgo, I., Soria, A. <[ftp://139.191.159.34/pub/EURdoc/eur20762en.pdf](http://139.191.159.34/pub/EURdoc/eur20762en.pdf)>.
- Lutsey, N., 2012. Comparison of emissions, energy and cost impacts of diesel and hybrid models in the United States in 2010. Paper presented to the 90th Annual Meeting of the Transportation Research Board, Washington, DC.
- Organisation for Economic Cooperation and Development, 2009. Fuel Taxes, Motor Vehicles Standards and Patents Related to the Fuel Efficiency and Emissions of Vehicles. Free Documents. Environment Directorate, OECD, <www.oecd.org/evn/taxes>.
- Organisation for Economic Cooperation and Development, 2011. Innovation and the Transfer of Environmental Technologies. OECD Studies of Environmental Innovation, Paris.
- Popp, D., 2002. Induced innovation and energy prices. *Am. Econ. Rev.* 91, 160–180.
- Porter, M.E., 1991. America's Green Strategy. Scientific American. April, 168 Economics Readings. Penguin Books, London.
- US Environmental Protection Agency, 2013. Light Duty Automotive Technology, Carbon Dioxide Emissions and Fuel Economy Trends: 1975–2012. <<http://www.epa.gov/otaq/fetrtwends.htm#report>>.
- US Federal Reserve Bank, 2012. Table H.15 Selected Interest Rates. Data: 1970–2012.
- US Department of Transportation, 2012. Summary of Fuel Economy Performance. Washington, DC.
- Yergin, D., 2010. The Quest: Energy Security and Remaking of the Modern World. Allen Lane, London.