Creating innovation through environmental policy: Evidence from OECD engine patents

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Creating innovation through environmental policy: Evidence from OECD engine patents

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An invention, when applied for the first time, is called an innovation. Resembling a tree that sustains branches, this paper identifies the factors which sustain complementary innovations of vehicle engines during 1974-2010 in the OECD region. A data set of 26,378 patents is used to estimate the impact on innovation of past energy prices, of legal limits on engine fuel efficiency, of non CO_2 standards, of consumer demand and cost of capital. The innovation models emphasise state actions that create innovations by technology push: public R & D expenditure and non CO_2 emissions limits. The models capture market pull sources of engine innovation. The first model confirms that observed innovation (diesel engine design) varies positively with state intervention via CO_2 standards and public R & D funds. Both a) the introduction of the EU Voluntary Agreement and b) lower capital costs magnify the growth of innovation. In the second model, observed innovations (pollution control) respond to OECD pollution standards and to diesel prices. (The impact of NO_x emission standards on pollution control innovations differs between Japan and the US). Corporate size, high energy prices and market power favour innovation within Japanese firms.

Key words: innovation studies, vehicle engines, economics of innovation, corporate R & D performance

1. INTRODUCTION

The study examines the period of 1974-2010 and it has three-goals: 1) to assess the effects of supply (i.e. R&D expenditure of transport) and demand (i.e. sales of diesel using vehicles and diesel trucks) factors on the rate of growth, and direction, of innovation in vehicle engines, in particular, for diesel types; 2) to test the induced innovation hypothesis: changes in a) policy design (i.e. standards of local pollution and of fuel efficiency limits on new car engines) and b) changes in relative prices spur the rate of innovation.

An invention when applied for the first time is called an innovation (Mansfield, 1969). One of the many ways to measure innovation activity is through the filings of patents for a single or a set of technologies. A patent is a set of exclusionary rights (territorial) granted by the State to a patentee for a fixed period of time (usually 20 years) in exchange for the disclosure of the details of a given invention (OECD, 2011).

Figure 1 shows the time trend of technological change (or innovation broadly defined) surrounding the diesel vehicle engine within 1974- 2010 years.

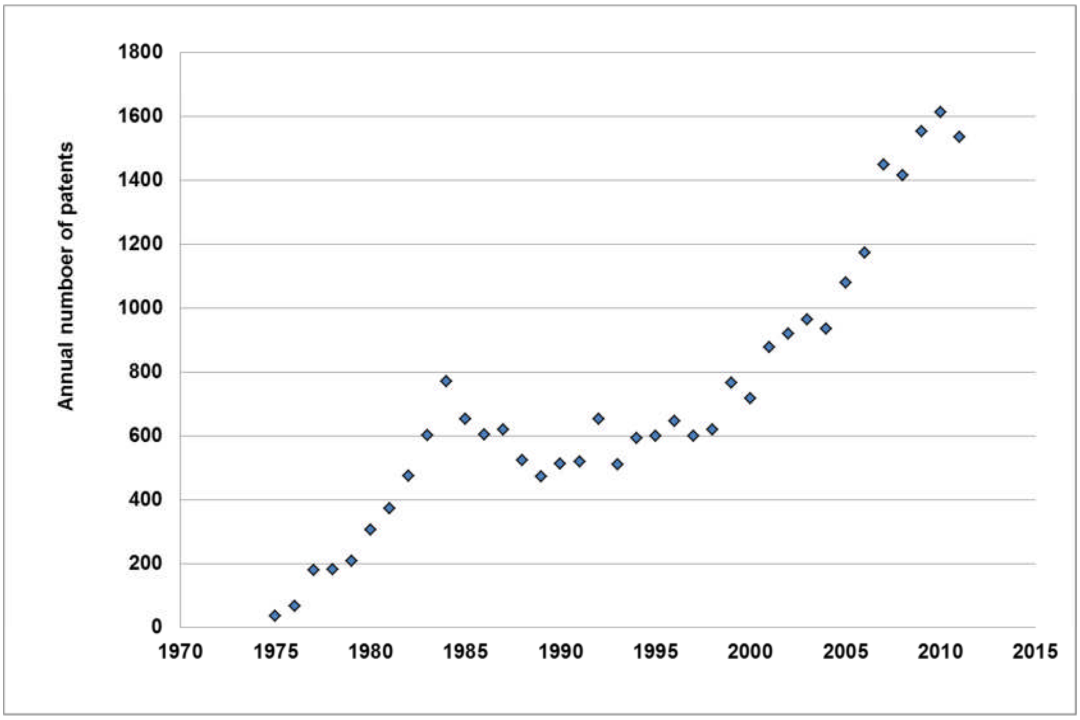

Figure 1. Diesel Patent Counts: US, Japan, EU and rest of the world. The data set used are grouped by "diesel engine" category. Annual number of patents by date of publication. Product characteristics of diesel engines change in 1974-2010. Sourced by the authors from the EPO (2012). This includes innovation: diesel engine design, air pollution control and fuel quality.

This technology (fig. 1) is associated to poor air quality but also to superior fuel economy (litres per km travelled of passenger vehicles), vehicle power and speed (Hivert, 2011; Bonilla 2009; Schipper and Fulton, 2010). Innovation, however, is needed to further improve engine performance.

As far as innovation, the Economist writes:

"the horse and sailboats were replaced by railways and steamships. Internal combustion engines and jet turbines facilitated movements of goods at a faster speed than it was 50 years ago; highway travel is a little faster than it was 50 years ago, indeed endemic congestion has many cities now investing in trams and cycling lanes" (The Economist, 2013). This passage indicates that the world's transport systems may transition towards both faster and slower forms of transport and it is unclear how diesel engine innovations will respond to those changes. Besides the hybrid diesel car there have been no radical innovations of vehicle engines in the past 5 decades. A radical innovation is defined as “coming from outside the mainstream…These innovations can create structural change but in terms of their aggregate impact they can be small and localised, unless a whole cluster of innovations are linked together in the rise of new industries and services ” (Foxon, 2003, p.14).

An innovation is also 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 a product one or a process one (Foxon, 2003). Process innovation is any adopted improvement in technique that reduces average costs per unit of output despite the fact the input prices remain unchanged (Blaug, 1963). The distinction between process and product is an artificial one: A cost reduction process changes the product mix (Blaug, 1963).

A gap is filled in the empirical literature of innovation by combining supply and demand factors to explain innovation activity of: a) diesel engines, b) its engine design and c) pollution control innovations of non CO_2 emissions of these engines. The results of this study are best seen as the effect of complementary innovations. The sample period used for the analysis covers recessions which affects short run responses of innovation to a) the business cycle via vehicle sales, and to (b) the two energy crisis and the longest period of economic expansion (1995-2008) in the OECD region. All of these events triggered innovation. This paper's contribution is to examine the past to assess innovations.

The main sample consists of 26,378 patent counts, within 1974-2010, most of which originate from independent inventors, car firms and car components firms based in Japan, European Union and the U.S. Independent variables include 2 measures of energy prices, three measures of consumer demand (vehicle sales), one metric of public R & D expenditure (transport), two metrics of NOx (nitrogen oxides) emissions limits, and one of vehicle fuel efficiency standards. The year of vehicle sales is lagged two years for 1974-2008. Two models are built in this paper. One model tests whether technical change of engine design responds to oil prices, to public R & D expenditure, to vehicle efficiency standards, and more crucially to market size factors that reflect the demand for engine innovation. The second model tests whether environmental policies of air quality that have been enforced in the OECD (Organisation of Economic Cooperation & Development), expand the volume of innovations of engines.

1.1 Literature review & background

In this section the key background literature is discussed along with changes in a) innovation 1965 to 2010 and b) in public expenditure on R & D for transport. Empirical studies of innovation began in the 50s but its number has accelerated in the internet era in the 90s. The first empirical studies emphasise market (pull) factors at the expense of government instruments (R & D expenditure) (Schmookler, 1966). Other authors emphasise the role of technology "push" i.e. public R&D (Mowery and Rosenberg, 1979; Popp, 2002; Newell et al.1999) in innovation. Other authors find evidence of a link between environmental regulation and improved environmental technologies (Jaffe and Palmer, 1996; Lanjouw and Mody (1996). Lanjouw and Mody (1996) find environmental innovations are produced largely by Japan, US and Germany.

Fagerberger et al. (2012) report an exponential increase in research in innovation. They review 66 articles, dating from 1910 to 2011, on "innovation studies" instead of using the term "the economics of innovation" as traditionally done in economics. Fagerberger et al. (2012) also identifies 532 references as forming the core knowledge base of innovation studies. The works of economists are also found to be the most highly cited ones (see Fageberger et al, 2012, Table 2). However the works of sociologists and management experts are also key particularly for the new theory of innovation that rely on historical and sociotechnical analysis (Geels, 2002) [1]

The empirical literature of innovation has relied on econometric studies that are based on observed innovations. The factors that lead to innovation can be divided into supply and demand ones. Expenditure on R & D (already mentioned above), the cost of making something, the legal framework of the industry, attitudes of management, of workers and of the public; how firms in industry organise and manage their R & D; and how scientific activity is managed by Government

[1] In our view, there is not a single theoretical or applied research work that describes all aspects of innovation processes. Many of the econometric works cited here take a linear view of the innovation process and the recent innovation systems theory can not be expressed in mathematical form.

agencies and Universities. (Mansfield,1969). Additional factors include energy prices, competition in the car and truck markets, public policy, environmental regulations, the level of trade openness, legal limits on non CO_2 emissions, energy-climate policy and trade agreements, (OECD, 2011).

Popp (2002) tests an econometric model to explain innovation in energy technologies (including automotive innovations). Using dataset of years 1970 to 1993 with 11 innovation classifications, he shows that the key influences on innovation are the effect of knowledge stock, Government R & D expenditure, and energy price. Evenson (1993) explains innovation using variables to represent GDP, competition, export share, and the propensity to patent for the US case. Newell et al. (1999) examine innovation by testing the Hicksian hypothesis on induced innovation; the Hicksian argument holds that relative prices influence the pace of innovation. Using a time series dataset for innovation in automotive energy efficiency, Crabb and Johnson (2007) find evidence of a) a positive response of innovation to the U.S. domestic oil price and b) a negative one to changes in the cost of capital for the U.S. case.

Hascic et. al. (2009) find empirical evidence of a positive effect on vehicle engine innovation after changes in a) gasoline price and the b) introduction of pollution standards (Non CO_2 standards of car engines: nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), on board diagnostics (OBD) and engine efficiency) for key OECD countries. Nemet and Kammen (2007) argue for higher public R& D expenditure to stimulate energy innovation for the U.S with the exception of the venture capital and the fuel cell sectors. Grubler et al. (1999) find that innovation can lower learning costs of energy technology.

While most of the above cited writers use sophisticated econometric methods, those studies rely on aggregate data on engine innovations which has limits on their applicability in explaining the various types of engine innovations in specific technology fields. This article uses disaggregate data on engine innovations to strengthen empirical explanations of innovation, and it introduces the role of a) supply and demand, and b) Government R & D, oil prices, competition, vehicle sales, and emissions limits imposed by governments of key countries.

One large scale study by the OECD (2009) assesses vehicle engine innovations using by patents counts for years 1965-2005. In that study, four broad categories are selected: non CO_2 Emissions, input fuel, input-engine design, output (other fuel efficiency) (Table 1 shows subcategories of one of these four groups).[2]

For the "engine design" category, Japan shows a cumulative (1965-2005 period) share of 49.6%, U.S. of 14%, and the EU 37.4%, (and Germany: 28%, France 4.3%). Most of these innovations improve fuel economy: less Litres consumed per km driven by car). For fuel injection innovations, EU is a world leader (Germany takes the largest contribution in this region), followed by Japan and the US. Under the "engine design" heading, the "FIN" (fuel injection) and the on-board diagnostics "OBD" categories record the highest number of innovative activity. Besides "SRS" and "FIN" items (table 1) Japan is the world leader in innovations. In the pollution

[2] We also use these categories for our patent classification on diesel engine technologies.

control item (not shown in Table 1), Japan is again the top innovator followed by the EU.

In terms of categories, the input engine category contains a higher number of innovations than that of emissions control, and output (other fuel efficiency) innovations.

A total of 43,181 patents by the OECD study were identified for the vehicle engine category, working out at 1079 patent counts per year in 1965-05. In contrast to the OECD (2009) study, our data set consists of average annual patent counts of 670 (average: 1975: 2010) patents per year.[3]

Table 1. "Fuel input engine" category for innovations in 1965-2005 for the key innovating nations (In patent counts). AFR: air to fuel ratio; SRS= oxygen, NOx and temperature sensors; FIN: fuel injection; EGR=exhaust gas recirculation; OBD: on board diagnostics; IGT: ignition timing. Innovations in the listed categories reduce fuel consumption except for IGT innovations. EU member States includes France, Germany, United Kingdom, Spain, Sweden, Italy, and Norway. Source: OECD (2009) (cumulative patent counts).

Group:	Engine Design						Sum (patent counts)
	AFR	SRS	EGR	OBD	FIN	IGT	
U.S.	787	166	466	1928	1613	353	5313
Japan	2583	322	1584	11606	3414	1908	21417
Europe	1606	541	1190	5984	6140	700	16162
Others regions	121	5	48	48	57	12	
Total	5097	1034	3288	19566	11224	2973	43181.5

[3] Oltra and Saint jean (2009) report a cumulative figure of patents for diesel engines of 2500 for the 1990-2005 averaging 166 diesel engine patents per annum for seven vehicle makers. The total number of innovations reported by Oltra and Saint Jean (2009) is below ours since our study includes a larger number of manufacturers of cars and parts.

EU % Share	31.51	52.31	36.21	30.59	54.71	23.55	
JP % Share	50.67	31.13	48.17	59.32	30.42	64.20	
US % Share	15.43	16.08	14.18	9.85	14.37	11.86	

"EU" includes: Germany, Austria, Denmark, Belgium, Czech Republic, Spain, Finland, France, Great Britain, Greece, Italy and Luxembourg, Netherlands, Norway and Sweden. For pollution control, the EU records 4932.3 patents; U.S 2132.9 and Japan with 5165. The OECD (2009) study includes gasoline fuelled engines innovations.

The OECD (2009) study, however, does not give the exact year of the innovations. It builds three quantitative models of innovations: engine design, pollution mitigation and other fuels. It uses as explanatory variables: the introduction of non CO_2 standards, CO_2 standards, fuel prices and fuel taxes in the OECD regions. That study finds that fuel taxes have the largest role in diesel engine research. The OECD (2009) study omits both public and private R&D expenditures, a key innovation input, in their econometric specification. Given the above, our study explains innovation by using information of three key economies: Japan, US and the European Union. Unlike the OECD (2009) and Hascic et al. (2009) studies and the above writers, our study is based on data in the diesel engine fields.

It is important to explain, and indeed to encourage, the rate of innovation of diesel engines since transport activity is a major contributor to global non CO_2 and CO_2 emissions. For example, in the US case, transport accounts for 50.9 % of NOx emissions, 30% for VOC (volatile organic compounds), 61.8 % for CO, 2.7% for PM-10; and for 4.2% of PM2-5 in 2011 (Transportation Energy Data Book, 2012; Davies and Diegel).

Diesel engines have dominated the car market for over a century now (Grubler et al 1999); this means that innovation is essential since diesel fuel use (and fossil fuels) impacts on the environment, macro-economy and on geopolitics (Nemet and Kammen, 2009). [4]Moreover, diesel engine innovation can deliver large scale benefits since most of the energy consumed by world transport activities is oil based (Banister et al. 2011).[5] Innovation is also important in order to mitigate global warming effects and to reduce the cost of complying with regulatory actions by public policy makers on non CO_2 and CO_2 emissions controls. Diesel engine technology is well established in land, marine and air transport and that technology has led to technological lock-in effects, nonetheless, innovation in this field continues to grow. Many of the papers cited, however, focus purely on energy innovations and do not take into account energy and non- energy related innovations of engines.

1.2 Public expenditure on transport R & D activity in the OECD.

Public expenditure in RD & D (R & D henceforth) can facilitate innovation in diesel related engine technologies, although there is a time lag; the lag is needed to

[4] The large majority of diesel engine innovations spring from Japanese and the European Union based car makers and many of the diesel engines are used in trucks as well as passenger cars, shipping, trains, farm machinery, small trucks, and machinery for agriculture and building sectors.

[5] Technical improvements of fuel economy have come from fuel injection, on board diagnostics and exhaust gas recirculation.

engender the innovation. This R &D measure includes costs, (labour and other costs) capital expenditures and it excludes some, but not all, scientific and technical activities. Figure 2 shows the historical trends during 1974-2010 of R & D expenditures specific to transport.

The evidence shows that the largest amount of R & D takes place in a handful of countries; these countries are responsible for 97% of total public R & D expenditure globally (IEA, 2012). The subcategory of “on-road vehicles”, within the transport R &D expenditure category, takes the largest fraction. Disaggregate data on transport R & D expenditures are only available for 2009-10 years. The cited R &D statistics (figure 2), unfortunately, exclude private expenditure, where the role of Japan and the EU is important (see section 4)15

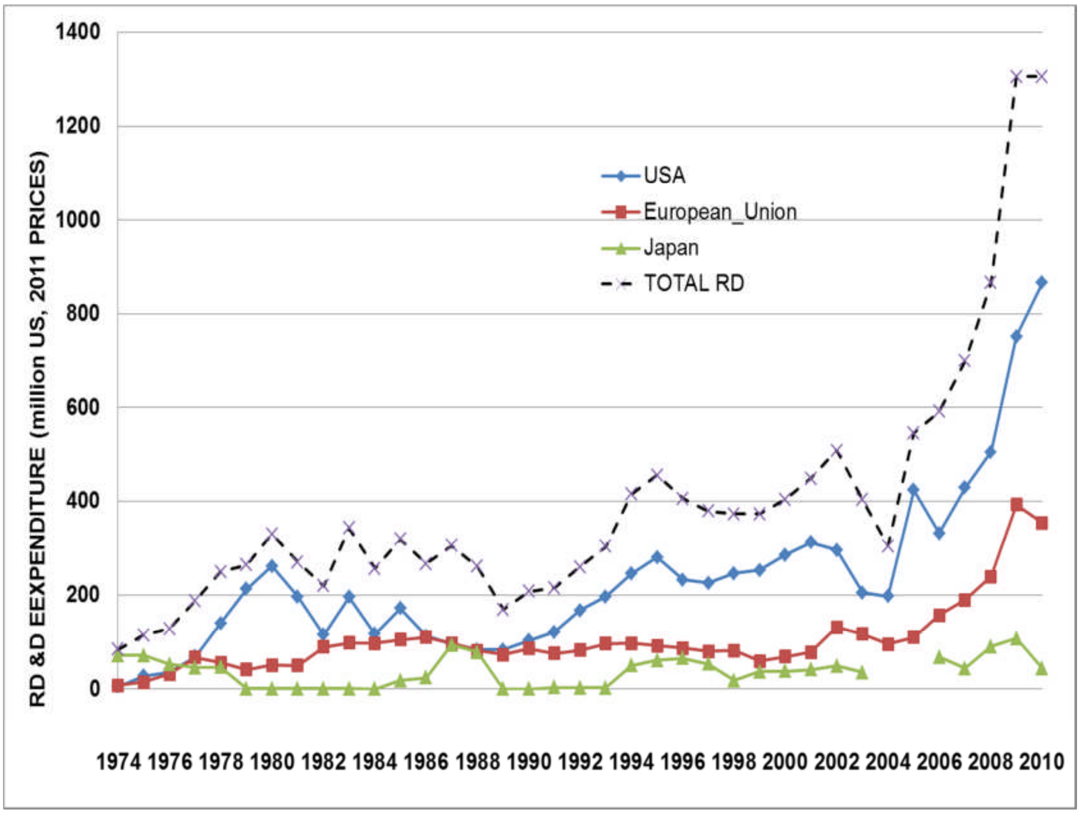

Figure 2. Expenditures on Research and Development in 1974-2010 for leading economies (Million USD constant 2011 prices and exchange rates). Source: IEA energy technology R & D statistics (2012). The data include only transport R & D. EU: Includes 21 European nations.

After the US, the key players are Japan, Germany and in future Korea and China (not shown in the graph) will emerge too. For private firms, the incentive to innovate can come from the need to compete in new product markets, the need to reduce costs of energy use; or from the need to reduce the effect of high energy prices. Historically, the US has shown the largest government expenditure levels in R & D as this is the world's largest economy. In the U.S., R & D expenditure was volatile but it peaks in 1990, 1995, 2005, 2010-2011 (Figure 1). These series of peaks in innovation should be correlated to the volume of vehicles sales in the same period.[6]

The US shows a strong increase in R & D in recent years (IEA, 2012) and this is probably due to the introduction of the American recovery and Reinvestment Act by president Obama in 2009, increasing R & D expenditure to 0.8 billion US $ dollars. This was a strong fiscal stimulus to counteract the effect of the 2008 financial crisis. The proportion of transport R & D expenditures has doubled since 2007 – 2010 specially for the U.S. and for the U.K., whilst Japanese R & D has been volatile but it peaks in 2009. EU R & D peaks in 2008. The US and Japan have been found to provide higher incentives for R & D activity than other countries (Eaton et al., 1998) but the EU has increased significantly R & D funds in the last decade.

[6] Transport R & D expenditure accounts for 17% of total R& D energy budget for the U.S; 1% for Japan and 6% for the entire European Union region in 2010. The U.S has always had the largest fraction out of the three regions in the period under study.

There is no doubt that this level of public expenditure in R & D for transport has benefited the growth of innovation in the sector; however, it is unknown how much of the increased transport R & D was channelled directly into diesel innovations for the entire 1974-2010 period. Section 2 discusses this further. R & D expenditure in transport comprises ten sub-classifications for transport R & D (according to IEA /OECD classification for R & D expenditures). [7]

To promote innovation many OECD nations use tax policy: The U.S. has stimulated company R & D expenditure since 1981 (US GAO, 1989) and the UK has only just done so in the early 2000 (under a UK Labour Government). This policy requires tax payer's money. R & D expenditures of the private sector (not included in figure 1) are determined by tax policy, merger policy, shareholder pressure, and incentive to research (The Economist, 2012).

It is common to examine the intensity of innovation by means of a ratio of total patented inventions (output) to total R & D expenditure (input). This ratio has declined in the US and in other advanced economies (Evenson, 1993; Nemet and Kammen, 2007), which reflects diminishing returns to R & D. For the transport sector, however, the overall trends in patents and in R & D expenditure do not show this (Section 3 discusses this point).

[7] Transport R & D **is** classified by the IEA (2011; "flow 13") as including categories of R & D 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"; "other on road transport"; "unallocated transport"; "off road transport and transport systems"; as well as other transport (IEA 2012;). The IEA does not report a breakdown for R & D investment of these classifications for all years but the "on road vehicles" item takes the lion share of R. & D in 2010.

In contrast to R & D in transport, overall R & D expenditure in energy efficiency has increased rapidly in Japan, Germany and the US. In Germany, R & D expenditure has increased more than 8 times in the last four decades, whilst in Japan it has done so by about 3 times albeit from a much higher base than Germany (IEA, 2012, data). The US has increased its expenditure considerably by about 50 times in the same period (1974-2010). This R & D activity has produced a number of innovations that indirectly support those in vehicle engines. [8]

The justification for R &D expenditure to enhance innovation meets four goals simultaneously: global warming , technological change, economic growth, and resource efficiency and employment.

2.0. Material and methods

In this section we discuss data on innovation activity of the diesel engine.

2.1. Data retrieval methods

The section discusses how the dataset was gathered on `supply "push" and demand "pull" factors of diesel engine innovations; the data are inputs into the econometric models of section 3. A full description of the econometric model of innovation is given in section 4. Most of these innovations discussed in this paper are not radical

[8] It is fair to say that many innovations have come from the broader public expenditure i.e. on basic research, education, etc. However, ideally the data should be modified to include EU expenditure on research framework programs. This paper focuses on the former category.

ones but incremental ones, that is, they do not break with past technological innovations. These are discussed below, following table 1 categories above:

The following innovations improve fuel efficiency of engines (OECD, 2009)

- Air to fuel ratio(AFR)
- Electronic fuel injection (FIN),
- Engine management systems, on board diagnostics, sensors (OBD),
- Ignition timing, variable valve timing, variable compression ratio (IGT), combustion chamber geometry,
- Engine performance during cold start accelerating,
- Combustion air and fuel conditioning.

The above list is included under the "engine design" category following the IPC(WIPO, 2012) categories for engine innovations. The patent data is sorted broadly in line with the above list. (The classifications are taken from the OECD (2009), in turn, taken from the IPC (WIPO, 2012).

Our dataset on patent counts, which represents innovation of diesel engines, is sourced from the European Patent Office which is accessed through the ESPACE (European Patent Office, 2012). This contains data for 90+ countries around the world. Using ESPACE, a series of searches for detecting inventive activity on a world-wide basis are made using key word searches. Our search results in a large number of patent counts recorded. Jamasb and Pollitt (2011) recommend using the key word search for technology level analysis.

The above search strategies returned 3 categories for diesel engines as well as subfields listed in the introduction (section 1). To identify the key sub fields of the patents, we used IPC codes in OECD (2009), in EPO, 2012 and in Hascic et al. 2009. The number of patents were sorted by the year of publication; this ensures that only successful patents are included in our data set. The data was classified for the 1974-2010 period but there was not always a consistent data series of patents for all subfields for every year.

Innovations that reduce local air pollution emissions (emissions control technology) include: crankcase ventilation, air injection, exhaust gas recirculation, thermal reactor, catalytic convertor, and particle filters. These innovations should react positively to air pollution (non CO_2) standards. These sort of innovations do not reduce fuel use: The adoption of the catalytic convertor and the introduction of improved exhaust gas reduction counteracted improvements in fuel economy (OECD, 2009).[9]

2.2. Disaggregated innovations of diesel engines

In this section a discussion is made on the type of innovations 1974 – 2010. Figure 3 shows the detailed breakdown of the innovations considered in this article. (Figure 1 depicts the aggregate number of diesel engine patents). The patent search included many engine components as indicated in the introduction.

[9] Exhaust gases result from the combustion of fossil fuels. Diesel engines emit higher non co2 emissions than gasoline engines, however the latter are less fuel efficient than the former. Exhaust gases are composed of carbon monoxide, nitrogen oxides (usually the main gas), particulate matter, and others.

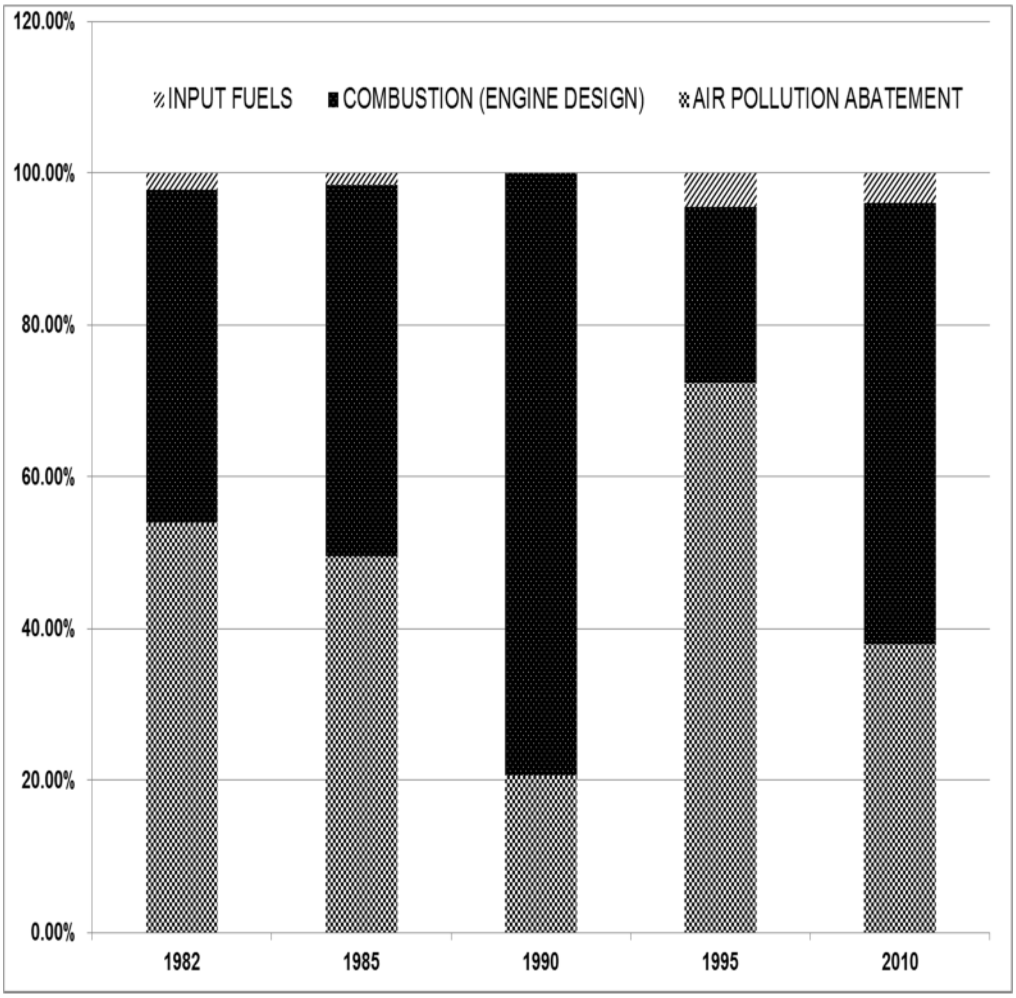

Figure 3. Innovations for vehicle engines (diesel). Sourced by the authors from the EPO (2012). Based on data on patent counts per year for the OECD region. For 1982: there were 461 patent counts; for 1985 612; for 1995 512The data excludes patents of gasoline fuelled engines, of alternative fuel vehicles and of aerodynamics. For 1990, the item "input fuels" is allocated to the engine design category. 1990 records 354 patents counts and 114 of diesel engine patents are unallocated for that single year. In 2010 there were 1250 records.

In fig. 3, the following events emerge: a) innovative activity in diesel engine design accelerates from 1982 onwards and this coincides with R & D Expenditures (R & D transport, Fig. 2) of private and public entities from previous years; innovation of this sort peaks in 2010 and it has the largest percentage contribution in all engine innovations. The share of pollution abatement innovation in total diesel ones has fallen in 1995-2010.

Figure 4 shows lagged R & D expenditure (transport) (US$ million constant 2011 prices and exchange rates) by one year and patent count data for 1974 to 2010.

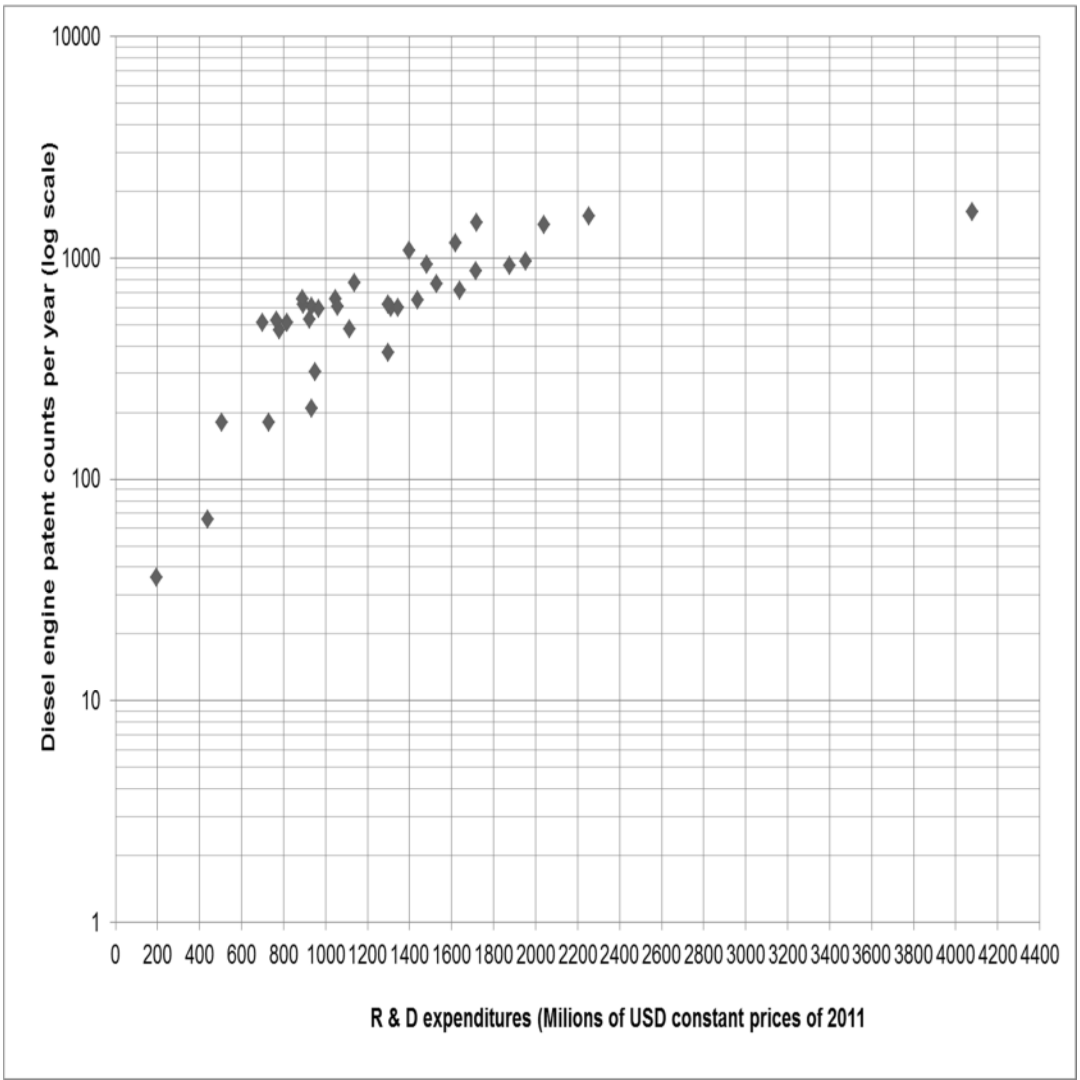

Figure 4. Patent activity and public (R & D expenditure for transport (in natural logarithms using data in millions of U$S dollars and patent counts per year) lagged by one year. The data shows a positive correlation between the expenditures and the level of innovation for most of the sample period. R & D expenditure includes the entire OECD region. Source: see figure 2.

The patent data (figures 1, 3, 4-5) are based on publication date which takes place 18 months after the patent is filed (OECD, 2005). This indicates the invention took place sometime before the patent is filed or its publication date. This means that microeconomic events that occurred (in the car industry) at least 18 months before the patent application date would be important in influencing the decision to innovate. It takes 4 years for an inventor to be granted a patent (OECD, 2005).

The link between patent counts and this kind of R & D is positive for most of the sample but not for every year (Figure 4). The higher the level of R & D is the higher the number of innovations there will be.

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2.3. Trends in diesel patents intensity

The ratio of patents for diesel engine per thousand US$ of R &D expenditure has grown at a slower rate in 1990-2010 than in the late 70s (fig. 5); in the 1974 – 2010 period (figure 5) the ratio doubled but its rate of growth declines in last 10 years, this indicates the multiplier effect of R & D public expenditure is declining.

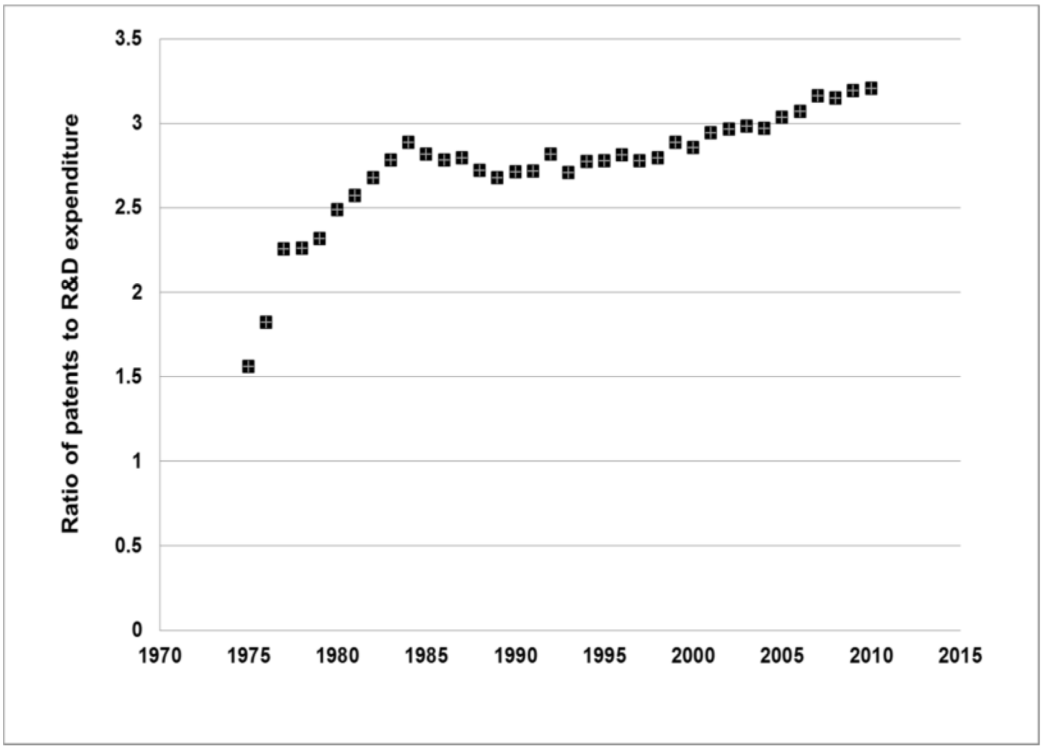


Figure 5. Innovation intensity (patents per R & D expenditure). Source: Elaborated by the authors based on figure 2 and EPO (2012). The ratio indicates R & D productivity.

From the mid -90s to early 2000 the ratio continues to increase in the OECD. This means both 1) the productivity of R & D improved but only slowly in the last 2 decades and 2) diminishing returns to investment in R & D expenditure for transport has not been reached yet and that 3) further increases in R & D may be worthwhile.

2.4. Data input and sample for innovation in diesel engine

Table 2 lists the input data that was used for the econometric analysis of innovations. During 1974 to 2010, patenting activity (mostly in Japan, EU and in the US) averaged 693 patent counts in a year; in the same period, transport R & D averaged

312 (millions of US $) for the total sum of OECD countries. Engine design innovation average 79% of all diesel engine innovations. The average inventor faced an oil price of 33 US$/barrel and a potential consumer demand, represented by vehicle sales, of 2 million truck units in Japan (and consumer demand in Europe for 23% of total passenger car sales). The average inventor also expected a) diesel prices of 0.41 (US$/litre) and b) a potential consumer demand for trucks sold in the U.S. of 5.8 million units.

Table 2. *Summary of data for the econometric analysis. Source: the authors*

Variable Name and Units	*Median*	*St. Dev.*	*Maximum*
Diesel patents (counts) (U.S., Japan and EU regions combined)	693.37	420.99	1612
Patents counts: engine design (fraction of all diesel engine patents) (U.S., Japan and EU combined)	0.79	0.05	0.89
Diesel prices (USD/litre (using purchasing power parity)	0.94	0.41	1.9
Oil prices(OECD average)US $	33	22	97
NOx standard (parts/million) (Japan)	113.22	171.82	450
Japan discount (loan) rate (Bank of Japan)(%)	3.34	2.7	9.0
U.S Treasury bill rate (secondary market discount basis) (%) U.S F.R.B.	5.62	2.99	13.16
EU Voluntary Agreement on fuel efficiency (dummy variable)	0.40	0.49	1.00
Public R & D expenditures Transport (millions US$, 2011 constant prices)	312.98	238.85	1134.98
Sales of Japanese trucks and buses (000s vehicle units)	1987.2	595.8	3003.6
Sales of US trucks and vans (000s vehicles)	5810	2414.5	9793
Sales of Diesel vehicle in EU (% share)	23.10	14.39	51.55
Source: diesel patents counts: EPO (2012); engine design patent: EPO 2012); diesel prices: IEA (2012); oil prices: IEA (2012); EU Voluntary Agreement: OECD (2009); R & D expenditures transport: IEA, 2012;			

Vehicles sales (trucks and buses) of Japan: JAMA, 2012; Sales of US trucks: Transportation Energy Data Book (2011); EU sales of diesel cars (JRC, 2002; Eurostat, 2012).

3. Model of Innovation and Methodology

We impose two models on the data described in sections 1 and 2. We estimate the effect on innovation of supply and demand factors for diesel engine research through two cases are examined below to explain engine innovation for 1974-2010. Table 2 gives the data employed.

3.1. Model of innovation for diesel engines

The following models are set up to test if the variables described in earlier sections influence the rate of innovation:

- Model 1: Diesel engine design (mainly fuel saving innovations);
- Model 2: Pollution abatement innovation of diesel engines. (exhaust emissions of: NOx, CO, HCs, PM, VOC)

The data was ordered using Excel's pivot option in order to visualise the entire set of patent information. Patent data was obtained for inventor, IPC class of patent, and name of company owning the patent.[10]

It is important to bear in mind that the models, listed above, are built to explain the decision to innovate by private and public entities.:

[10] The EPO Espace data base (EPO, 2012) provides IPC codes which allows us to order the data for pollution control innovations and for engine design.

In order to find out what drives innovation in the diesel engines, data on R & D expenditures are used as a proxy for the knowledge stock of the OECD economies. Popp, (2002) uses this metric to estimate innovation in the U.S. This analysis can capture policy effects on innovation in the entire vehicle industry (Classified as automobile and parts by the EC).

Equation 1 is used to estimate the decision to add innovation: engine design innovations for years 1974- 2010. The OLS regression is the following.

The model of engine innovation is represented by equation (1):

$$
\begin{aligned}
{epat_t}/{totdiesel_t} &= \alpha + \beta_1 (R\&D_{t-1}) \\
&+ \beta_2 (oilpOECD_t) + \beta_3 (EUSales_t) \\
&+ \beta_4 (JPSales_t) + \beta_5 (EUVA_{t-1}) + \beta_6 (loanR_t) \\
&+ \beta_7 (timetrend) + \varepsilon_t
\end{aligned}
$$

(1)

Where, *epat* represents the percentage of successful patents for engine design of total diesel patents per year, this is the aggregate of innovations for the "engine design"; *R&D* research and development expenditures for the OECD; *oilpOECD* oil prices for the OECD; *EUSales* ratio of diesel car sales of total car sales; *JPSales* sales of truck and buses in Japan and; EUVA European Union Voluntary Agreement for fuel efficiency of vehicles (0 for 1974-1995; 1 1995-2008); loanR loan rate in Japan; t stands for a continuous variable for 1975-2011. Epsilon stands for the error term or the unexplained part of the model.

Equation 2 is used to estimate the decision to add (pollution control) innovations for years 1984- 2008. The OLS regression for diesel engine design is given in eq. (2). This model includes a vehicle efficiency standards with car makers in the EU region on diesel engines introduced in 1995.

$$
\begin{aligned}
envpat_t \big/ totdiesel_t = {} & \alpha + \beta_1 \, (R\,\&\,D_t) \\
& + \beta_2 (diepOECD_t) + \beta_3 (StaNoxJP_t) \\
& + \beta_4 (StaNox\,US_t) + \beta_5 (EuroNox_t) \\
& + \beta_6 (EUVA_{t-1}) \\
& + \beta_7 (EUsales_{t-1}) + \beta_8 (FedUS_t) \\
& + \beta_9 \, timetrend + \varepsilon_t
\end{aligned}
$$

(2)

Where, *envpat* represents the percentage of successful patents for pollution abatement innovations of total diesel (*totdiesel*) patents; *R&D* research and development expenditures (transport) for the OECD; *diepOECD* diesel prices for the OECD;; *StaNOxJP* NOx emissions standard (Japan); *StanNoxUS*, NOx emissions standard (US); *Euronox* NOx emissions standard (EU); *EUVA* and *EUsales* are defined eq. 1); *FedUS* treasury bill rate (US) represents the loan rates; t, time,stands for a continuous variable for 1974-2008. Annual data is used for all variables.

Hypothesis to test (specific innovation equations):

- Hypothesis one: state intervention effects (via R & D and pollution control legislation) explain more effectively than vehicle sales (by effect of changes in consumer demand) the rate of innovation in diesel engines;
- Hypothesis two: oil prices determine the direction of innovation (induced innovation; market forces) in the sector and the effect of the home market (vehicles sales) is the strongest of the two pull factors.

3.2. Discussion and Results

The results of equation 1 and 2 are tabulated on tables 3 & 4. The engine design category, model 1 (equation (1), is explained by two coefficients: vehicle sales (or consumer demand), for two regions (EU and Japan) and by the effect of the EU Voluntary Agreement with car makers achieved in 1995. These three variables hold a positive effect on innovation (Table 3). A home market effect on innovation is reflected in the vehicle sales coefficient (Japan and EU) both of which are positive (table 3) but this does not apply for the US case (result is not in table 3). The truck and passenger car sales variables capture the short run effects of innovation to consumer demand. Sales are decisive in influencing whether or not a R & D program should receive funding and so the positive coefficient confirms this.

The second finding is that the innovator is not crowded out by public R & D expenditure; this indicates that public funding for R &D stimulated innovation in that period. Lower loan rates should encourage innovative activity and the coefficient shows the correct (a negative) sign, (even if it is not statistically significant). This effect is important since the capital market provides funding for innovators.

The third finding (Table 4) is that the effect of diesel price discourages pollution control innovations since they relate to non energy saving innovations. The effects of two variables (diesel car sales and of public R & D) reduce the rate of innovation in pollution control in addition to price. Unlike the engine design case, the effect of public R & D expenditure crowds out pollution control innovations.

The introduction of the NOx emissions standards (of Japan and of the US) on engine innovation holds a positive effect (table 4). The effect of the Euro NOx standard is smaller than that of the two other NOx standards, however, the effect of the standards is consistently positive.[11] The effect of the EU voluntary Agreement on pollution control innovations also shows the right sign since there is usually a trade off between improving fuel economy (engine design) and pollution control technologies. The effect of diesel prices (inclusive of taxes) is non-positive: high prices discourage innovators since they expect vehicle buyers to demand fewer of these, and in turn, demand for vehicle engines innovation should fall. The effect of market demand on innovation does not show a positive effect because these innovations preceded the development of consumer demand for vehicles. The capital market effect through the loan rate shows that lower capital costs encourage innovation. This effect is the same as in the engine design innovations (eq.1).

Table 3. *Regression results of diesel innovation* **(***dependent variable: percentage of patent applications of engine redesign in total diesel engine patent applications.) Sample period: 1974-2008. See previous table for units of variables.*

Independent Variable	**Effect of direction;** t-values in brackets.	**Adj. R sq.:** 0.70 Durbin Watson: 1.39; No. of observations: 32	**Functional form**: regression in levels.
Public R & D (transport) (1 year lag)	Positive 0.10 (0.556)*		
Oil Prices	Negative 0.001; (0.92)		

[11] Japan' s NOx standard is introduced in 1974; US NOx one in 1976; and the Euro NOx limit diesel in 2000. (OECD, 2009).

EU diesel Vehicle Sales (ratio of total vehicle sales) (1 year lag)	Positive 1.98 (3.30)***
Sales of trucks & buses (Japan)	Positive 0.60 (2.14)***
Loan rate (Japan)	-0.23(0.814)
EU voluntary agreement on fuel efficiency limits (1 year lag)	Positive 0.7 (2.18)***
Time trend	2.77 (5.77) ***
*** indicates statistical significance at less than one % level, ** at less than five percent level; and * at less than 10 % level.	

Table 4. *Regression results of emissions (pollution) control innovation* ***(****dependent variable: percentage of patent applications of pollution control of total diesel patent applications****)****. Sample period: 1984-2010***. **Source: the authors.** *See Table 2 for units of variables.*

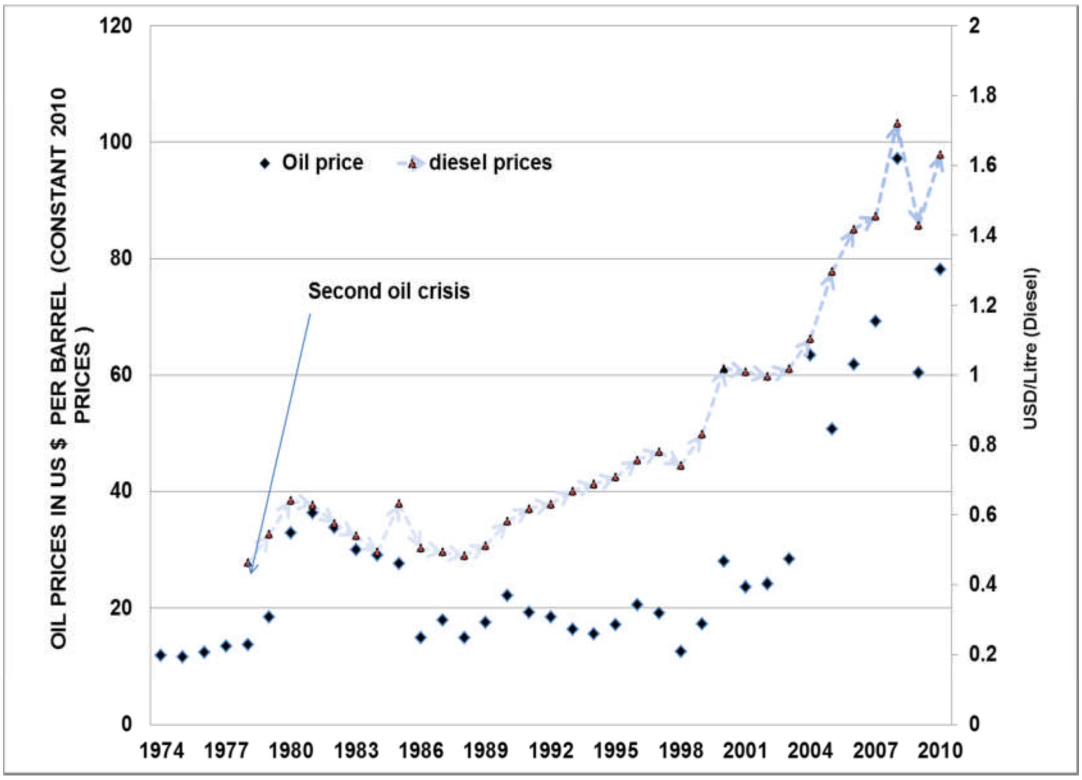
Independent variable	Direction of effect & (t-values in brackets)	R Sq.: 0.724 DW: 1.95. Observations: 26	Functional form: Regression in levels.
Public R & D (Transport)	Negative -0.70. (-2.87)***		
Diesel prices (OECD Average)	Negative -0.52 (0.92)*		
Sta.-NO_X emissions (Japan) (parts/million)	Positive 0.252 (1.67)*		
Sta. –NO_X-HC emissions standards (U.S.) (Kg/km)	Positive 0.44 (1.34)		
EURO NO_X	Positive 0.176(0.613)		
EU Voluntary Agreement with car makers	Negative -.542 (-1.71)*		
EU diesel car sales (ratio to total car sales) two year lag	Negative -1.71 (-2.59)**		
U.S Treasury bill rate (secondary market discount basis) U.S	Negative -0.58(2.00)**		
Time trend	3.3 (4.28)***		
*** indicates statistical significance at less than one % level, ** at less than five percent level; *marginally significant at 10%;			

4. Broader economic factors for innovation.

This section discusses the changes in supply and demand pressures on the car industry and on independent innovators to innovate. The section describes the economic landscape for innovation in relation to: oil prices (OECD average), private R & D, competition in the car market, environmental policies for emission control.

4.1. Oil prices in the OECD as a factor of innovation

Expectations on oil prices levels (figure 6), also support innovation activity. [12] In the 2000-10 period, the oil price level has quintupled and this period sees a sustained



[12] Popp (2001, 2002) uses data on oil prices as a control variable for innovations for several energy technologies; Hascic et al. (2009) and OECD (2009) use fuel prices; Crabb and Johnson (2007) use domestic and foreign oil prices.

Figure 6. Oil prices (OECD AVERAGE: Europe, U.S., Japan). Prices are an incentive to innovate in fuel economy of vehicle engines. Source: IEA, 2011. (constant 2011 US$/barrel of oil). Diesel prices include taxes (right hand axis).

rise in oil prices that supported engine design innovations simultaneously (figures 1 & 3, 6). In contrast to 2000s decade, prices had been stable in the previous two decades (80s and 90s).

An additional factor for innovation is the general energy price level (mentioned above) since firms (innovators) and economic agents will react to potential profit opportunities from energy saving possibilities. Energy saving possibilities, in turn, will depend on the rate of innovation. Those possibilities, and sales of cleaner and more energy efficient engines, will depend on the future expectation on the energy price level. Energy prices also determine the cost of running a vehicle engine.

4.2. Private R &D expenditure by firms and competition

Another source of support for innovations is the level of private R & D expenditure (mentioned above); the levels of public R&D transport (figure 2, section 1) are far smaller than private R & D expenditures. A snapshot of R & D expenditures provides a guide on the global rank of leading innovators. Table 5 lists the levels of private R & D, share diesel patents by major vehicle manufacturers and their global car market share. Unlike the trend in public R & D expenditure for transport where the U.S. leads, U.S car makers do not spend more on R & D than Japanese ones. In

2008 Japanese firms spent the largest amount on R&D (18 U.S $bn.); this is more than any other competitor; the position of German firms as a whole comes last.

Table 5. Private R & D Expenditures (in 2008) and market shares.

Maker	**Expenditures on R & D (2008) (Millions of US$ Dollars)**	**% share of total diesel patents**	**Car Market share**
1. Toyota	8994	26.8	13.4
2. General Motors	8000	2.0	12.1
3. Ford	7300	3.1	7.88
4. Honda	5142	1.2	5.7
5. Volkswagen	4757	3.00	9.3
6. Daimler	4321	6.00	3.1
7. Nissan	4001	22.1	4.95
8. Renault	2531	2.8	3.5
9. Mitsubishi motors	0.240	19.10	1.9
10. Hyundai	3000.0	10.5	4.0
11. Rest of world	Na.	Na.	40
The top 8 firms capture about 60% of the global car production market; the rest of the car makers account for 40%. Source: data on % of Diesel patents by car maker in Oltra and Saint Jean (2009); for car market share in OICA (2012) for 2010. Hyundai R & D data in Bloomberg (2009).R & D funds in thetruthaboutcars.com (2012).			

Japanese car makers (Toyota and Nissan, Honda) are global leaders in the field of R & D expenditure for automotive technology (Table 5). European car makers show lower expenditures but this list excludes R & D expenditures by vehicle component manufacturers located in Europe. It is possible that European car makers spend more on R&D than their non European competitors.

The top expender (in 2008), Table 5, is Toyota followed by General Motors (GM). This level of expenditure is likely to be correlated with patenting activity of diesel engine technologies and of drivetrains. It should be remembered that a dollar spent in say, Toyota, does not equal a dollar spent in Renault nor in General Motors and national definitions vary on what constitutes “Research and Development”.

The historical spending level per car manufacturer provides an additional indicator of patenting activity, however, many car manufacturers do not publish a detailed breakdown of their R & D activities. In 2009, private expenditure on R & D in the EU for category of “automobile and parts” reached 70 Billion Euros (EC, 2010). This category includes car maker firms from outside the EU in addition to European car makers and parts making firms. In that year, Japanese firms did not reduce their R & D expenditures as much as American and European car firms did; although the latter reduced expenditure to a lesser degree than US firms. This means that EU private R&D was negatively affected mainly by US firms based in the EU. It is unknown how much of this R & D expenditure was channelled into diesel engine car makers in the EU.

A third source of support for innovation is the market structure of the car industry, which is mainly affected by the intensity of competition among car makers. The Herfindahl - Hirchsman (HHI) index (U.S. DOJ, 2012) measures the level of competition in the car sector. The index should tend to zero in a competitive market and to 10.000 in highly monopolised market. For the EU, the index reveals a stable level of competition from 1975 to 2008 (Table 6).

For Japan, the top innovator (Table 6), the index shows increasing market power (or firm size) in the Japanese car industry as the index approaches 1775 levels. For the EU market, the HHI shows less concentration of market power than Japan does. Generally, the US car sector shows similar levels of competition to those of the European Union, (with an 1169 index level), but this level of competition has not translated into more innovative activity for the U.S. The evidence shows that bigness is associated with innovation since the Japanese firms shows higher levels of R & D expenditures and engine innovation than U.S. ones.

Table 6. The Herfindhal and Hirschman index of market concentration for car makers for selected economies and leading innovators. Calculated by the authors using JAMA, 2009; Eurostat website and the US sources. For Japan, the figures are based on vehicle production statistics, for the EU on vehicle sales figures. For the US, see source http://online.wsj.com/mdc/public/page/2_3022-autosales.html#autosalesE. For the US case, the HHI index is based on data in Train (2007).

Countries	1975	1990	2008
Japan	1104.5	862	1775.0
The European Union		1067.1	1193.6
The United States	2628	2022	1169 (2011)
Average (3 regions/countries)	1866	1317	1379

As some authors have argued (Schumpeter (1932); Mansfield, 1969) the largest firms are usually the ones that can innovate and for this reason we focus in this section on the world largest car makers.

For 2005, Japanese car makers such as Toyota, Honda and Mitsubishi (combined market share of 69% using patent data) top the league in diesel engine innovation. In 2005, the leadership of Japanese firms, in diesel engine innovation does not shift. The evidence of Table 5 shows that Japan, and European car makers, hold the key to explaining innovation in diesel engines since these car makers are the largest private R & D expenders (Table 2). In the global ranking of public R & D, these two regions are also important leaders (Figure 2). The R & D levels of expenditure explains innovation to some degree: Basic research (through R & D expenditure) yields scientific knowledge, which in turn, generates technologies, which in turn lead to practical applications. This is, however, a linear model of innovation.[13]

As said before, Japanese car makers continue to be the market innovators in terms of the total volume of innovations, of R &D expenditure at the firm level.

4.3. Non CO_2 emission standards, public policy & innovation

[13] An alternative explanation is that innovators are no longer patenting all of their innovations and so general patent data may not capture the entire true sample of innovations. Innovation may still be increasing for some car firms but alternative data is needed to capture new innovations. Our sample may suffer from “hidden evidence bias”. The opposite can also be true: entrepreneurs are not innovating as much as they used to.

A fourth source of innovation is the introduction of public policy measures such as vehicle pollution standards, CO_2 emission standards and OBD legal requirements. These were first tightened during the 70s in the U.S, in Japan and in the EU (Hascic et al. 2009; Zhu et al. 2006). In Japan, exhaust standards were introduced in 2000 along with OBD (Hascic et al. 2009). Public policy has a strong role to play in supporting financially and legally the rate of growth of innovation.

Some patent categories used (fig 7) here are correlated to emission standards (non-Green House Gas standards) affecting engine design. Other categories are not correlated at all. For example, the growth in catalytic converters technology is correlated to emission standards for nitrogen oxides (NO_X) emissions.

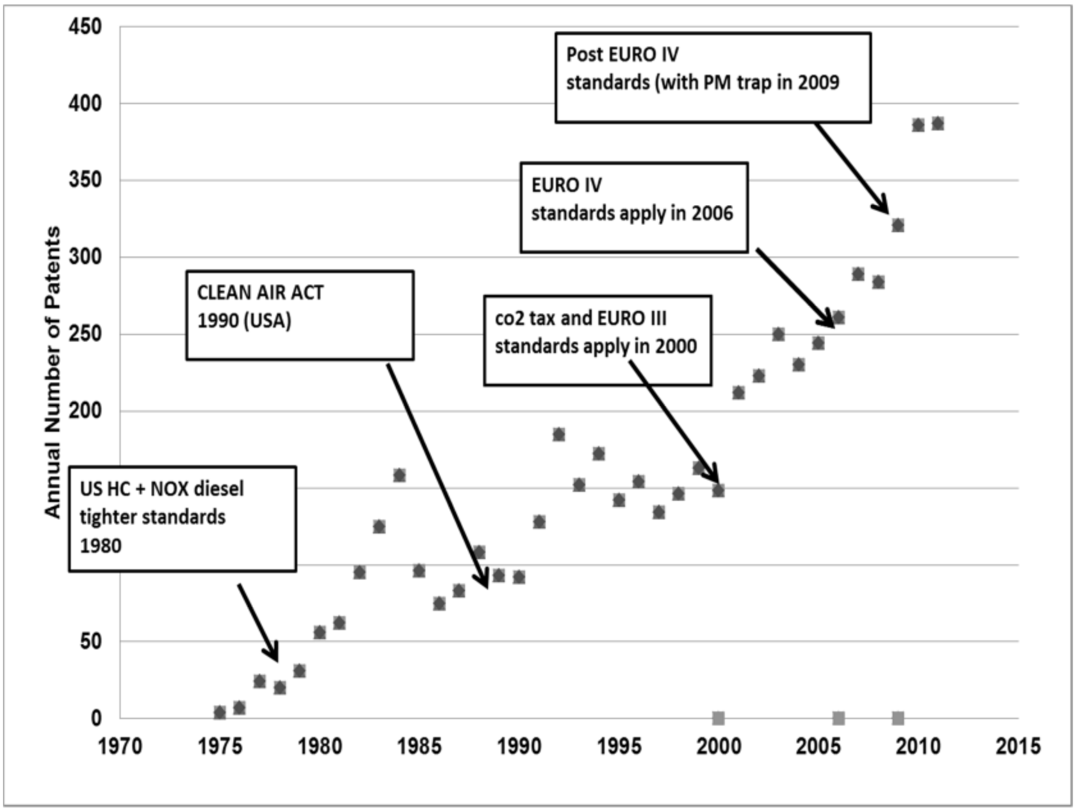


Figure 7. Pollution control innovations for engines: "Diesel and exhaust gas" category. Patent counts sorted by the publication date. This covers 90+ countries.

These standards were introduced in in different years, the 80s and 90s, by the US, Japan and in the European Union; the latter has set the least strict standard (NO_X grams/km driven) since it has a large diesel car stock. Japan and the US have the lowest shares of dieselisation of their passenger vehicle fleets and have stricter standards on NO_X emissions than the other regions. The latter two nations do have large stock of diesel powered trucks and buses (JAMA, 2012).

The evidence of figure 7 confirms that state intervention through the emission standards that were introduced in the 80s throughout the OECD in the 90s until 2010, led to technological innovation.

The timing of environmental policy was important to improve the level of innovation of the diesel engine. There were a series of policy changes in the 1974 2011 period, as Figure 7 shows, that are associated to the increase in innovations that reduce exhaust gas emissions (mainly NO_x ones). In the U.S, the first standard is the HC (hydrocarbon) and the NO_x diesel standard in 1980; an exponential increase in innovations in this field can be seen (Fig. 4) after that year. The Clean Air Act (of the U.S) in 1990 also led to emissions abatement innovations a year after. In the EU, there were a series of abatement controls introduced by authorities (Euro III, EURO IV, Post Euro IV) associated to the growth in emissions abatement innovations. In Japan the NOx standard was introduced in 1976 and tightened in 1978 and in 2000 (data in: Hascic, et al., 2009). By 2005 Japanese authorities had tightened the NOx standard from 450 part per million to 0.15 (grams/km) and in the US Nox-HC standard from 6.6 (grams/km) to 1.05 (grams/km) by 2005 (data reported in OECD, 2009).

Figure 7 shows that in 2010 1/4 of all diesel engine patents (fig. 1) were related to the “diesel exhaust gas” category. To gather data on pollution abatement innovations a search string is used to retrieve data in EPO (2012); our search relies on the keyword “engine” in the title and “vehicle engine and exhaust” in the abstract of the patent.

In short our empirical evidence shows five sources of innovation: sustained increases in energy prices (or taxes), R & D by private or public firms, weakening competition overtime of car makers and environmental laws controlling CO_2 and non CO_2 emissions limits imposed by public policy makers.

5. CONCLUSIONS

The role of government via pollution limits and public R & D funding can be a potent force to stimulate engine innovation and the latter can deliver many benefits such as motor fuel savings, global warming mitigation, health protection, employment and resource efficiency. Our data confirms that Innovation of diesel engines has followed the introduction of (1) non CO_2 emissions standards (NOx emissions controls), (2) of vehicle fuel efficiency. The standards have forced the take up of energy saving innovations for engines. Further cuts, however, in CO_2 and non CO_2 emissions of diesel engine are needed since diesel vehicle traffic and road freight transport continue to grow and the political pressure to mitigate global warming and to protect public health increases.

Our evidence shows that the decision to innovate in energy saving techniques is explained, first, by movements in key variables: public expenditure on R &D and the introduction of the EU voluntary Agreement. OECD (2009) reports the same result for the direction of the latter effect. The effect of public expenditure on innovation mimics the findings of Jaffe and Palmer (1997). Further effects work operate through the growth of vehicles sales and of oil prices. Popp (2002), Crabb and Johnson (2007) find the same effects for the US only. The time trend effect is large suggesting that some unobserved effect is present in the decision to innovate. The effect of market pull (of Japan and of the EU), outweighs that of public expenditure on R & D, however, the latter benefits innovation indirectly. This market effect is explained by the dominance of private innovators rather than public enterprises.

The decision to add an innovation, as far as emissions control, shows no evidence for (a) market demand effect, nor (b) of a direct effect of public R & D. Both of these factors are negatively associated to that decision because innovation preceded the growth in the market for trucks and cars. The effect of diesel prices is also negative which reflects that innovators are discouraged when these face higher fuel prices since these assume there will be lower consumer demand for diesel vehicles under rising prices. The decision to innovate is positively linked to the introduction of NOx emissions standards of three regions considered here reflecting that some innovations increased after the fact; this confirms the findings in OECD

(2009) but our study excludes gasoline fuelled engines. Our models, however, assume a linear relationship between inputs and outputs which may not always be the case.

The broader evidence shows that seven domains explain the rate of innovation of diesel engines: Oil prices, potential truck sales, private R & D expenditure and market power in the car market. Other less quantifiable factors that influence innovation in fuel saving techniques include: global carbon agreements, trade and tax breaks engineered by public policy. We find that the intensity of patent has slowed down in the OECD but most of the R &D is conducted by private firms based in three regions.

Further research should focus on the role of public and private actors in the innovation chain using a broader definition of R & D inputs and using alternative metrics to capture generation of innovations. A nonlinear framework should also complement our models.

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