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Fuel Prices and Environment-Friendly Innovations. Evidence from the Automobile Industry

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Abstract: This paper empirically examines the relationship between fuel prices and patenting activity in environment-friendly technologies in the auto industry across the OECD countries for the period 1994-2011. Overall, the results suggest that tax-inclusive fuel price affects innovative activity in environment-friendly technologies. More specifically, the analysis shows that the technologies aiming to reduce the amount of fossil fuel combusted by vehicle are induced by fuel prices. Thus, innovations in *electric* and *hybrid propulsion*, as well as innovations aimed at *the improved fuel-efficiency* are fostered by rising prices. At the same time, the estimation results suggest that innovative activity in *the integrated emissions control* is negatively affected by fuel price and by the stringency of policies. Whereas innovations in *post-combustion technologies* are insensitive to price changes and are fostered by the toughening regulation.

Key words: Induced innovation, technological change, auto industry

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1. Introduction

Growing environmental concerns of recent decades mean that patterns of energy use should be reconsidered. Current objectives of policymakers worldwide include decreasing dependency on oil and reducing carbon dioxide emissions (OECD, 2011: 20). To comply with the toughening policy targets, the industries around the world have to develop sound strategies for R&D and production. In the automobile sector, which accounts for a substantial share of local air pollution and greenhouse gas emissions in the developed countries, several approaches to addressing policy requirements have been established (OCED, 2011: 60). First, transport sector recognizes that policy objectives can be met through electrification of vehicle propulsion (IEA, 2013: 2). Two types of *alternative propulsion* systems that utilize electricity – hybrid and electric propulsion – are considered as environment-friendly technologies that can play an important role in transitioning towards greener use of energy in the industry. Secondly, the amount of pollutants released in the atmosphere can be reduced by *redesign of conventional internal combustion engine* (Haščič et al., 2009).

Transition towards more environment-friendly technologies has recently acquired greater attention among scholars. Research efforts are put to analyze the role of technological progress in this transition. On the whole, the theoretical models that treat technological progress as endogenous, predict that the amount of innovations generated by market will be insufficient for mitigating climate change and greater investment will be directed towards technologies causing the escalating pollution (Pizer & Popp, 2008). For instance, Acemoglu et al. (2012) suggest that innovations are path-dependent in the sense that producers in the economies, which have previously invested a lot in 'dirty' innovations, will be more likely to continue investing in 'dirty' technologies later, rather than switch to more environment-friendly ones. This theoretical prediction implies that market forces are insufficient to redirect investment from disruptive towards cleaner innovations, government intervention is needed.

The automobile industry is among the major contributors to local air pollution accounting for about 50% of carbon monoxide (CO) emissions and 35% of nitrogen oxides (NOx) emissions across the developed countries (OECD, 2007). The industry accounts for approximately 25% of greenhouse gas emissions across OECD (OECD, 2011: 60), Moreover, the share of hydrocarbons released in the atmosphere by the auto sector is around 21%, while the proportion of particulate matter contributed by the sector accounts for around 12% (Haščič et al., 2009). The ability to diminish the emission output generated by the automobile industry would have a substantial environmental impact (OECD, 2004: 4).

At present two streams of innovating activity in the auto sector are devoted to the environmental issues: technologies directed at lower emissions output and at higher fuel efficiency. Recently the OECD committee on Environmental Policy and Technological Innovation (EPTI) has developed a list of technological areas in which innovations are believed to have a promising environmental impact in relation to the climate change mitigation (OECD, 2011: 191). For the auto industry this list includes three technological areas: technologies devoted to the *alternative propulsion* (*electric or hybrid)*, technologies directed to the improved *fuel-efficiency,* and technologies related to the emissions abatement in *internal combustion engine*. Better understanding of factors that drive innovations in these technological areas would shed some light on the measures, which can be taken to mitigate climate change.

In an attempt to ensure the transition towards more environment-friendly technologies policymakers develop different strategies. A variety of the introduced policy measures inspired a body of literature examining the evolution of technologies in response to changes in economic conditions (known as *technological change literature*). Even though, a lot of efforts have already been put to investigate the factors affecting technological change, both policymakers and scholars agree that there is still a need for better understanding of the determinants of environment-related innovations (Pizer & Popp, 2008; Popp et al., 2009; Haščič et al., 2009).

1.1. Research question

Empirical examination of technological change and its determinants is to a large extent related to the Hicks' hypothesis of induced innovation. In particular, according to Hicks' proposition, an increase in the relative price of one production factor stimulates innovation directed to the decreased use of this relatively more expensive factor (Hicks, 1932: 124). Recently this hypothesis has received greater attention in environmental studies, which examine how energy-saving technologies respond to changes in energy prices (e.g. Popp, 2002; Verdolini & Galeotti, 2011; Jang & Du, 2013). The analysis of the effect energy prices have on the energy-saving innovation has clear policy implications, as it improves understanding of the way policymakers can influence the incentives of manufacturers in order to mitigate escalating environmental concerns.

In application to auto making the induced innovation hypothesis can be interpreted in the following way. As regards '*the production factor',* it is standard in the environment-related literature to consider *fuel price* and it is usually the fossil fuel which is analyzed (e.g. Newell et al., 1999; Popp, 2002, Aghion et al., 2014). Thus, for the auto sector, petrol and diesel price are in focus. Next, the hypothesis posits that an increase in fuel price stimulates innovations that use lesser amount of fuel. In application to the automotive industry, lesser use of fuel can be achieved by higher fuel efficiency. From the perspective of technological progress in design of motor vehicles, higher fuel efficiency can be achieved either through improvements in the engine design or through the implementation of the alternative propulsion systems. Therefore, both fuel-efficient technologies in internal combustion engine (ICE) and alternative technologies that substitute ICE (i.e. electric and hybrid propulsion) qualify as the energy-saving technologies in auto industry.

Thus, according to the induced innovation hypothesis, rise in fuel prices spurs innovation directed to the alternative propulsion systems and at the improved fuel-efficiency. Aghion et al. (2014) offer an additional theoretical consideration to this hypothesis. In particular, the authors argue that innovative activity in technologies specific to ICE, excluding those directed to fuel efficiency, declines, when fuel prices rise. In other words, according to the study, innovations in ICE, which are not devoted to the improved fuel efficiency, are suppressed by rising fuel prices. The study labels these technologies 'dirty' and shows that rising fuel prices decrease profitability of 'dirty' innovations, and, therefore, discourage manufacturers from investing in ICE-related technologies. As a matter of fact, technologies directed to a reduced emissions output in ICE qualify for this category, as they are not necessarily fuel efficient (OECD, 2011: 88). Overall, the discussed theoretical considerations imply that rising fuel prices encourage innovations in alternative propulsion and in fuel efficiency, while they discourage innovations related to ICE (excluding fuel efficiency developments).

This study intends to improve understanding of the determinants of environment-related innovative activity in the auto sector by testing these theoretical predictions for the three above mentioned technological fields. In particular, first, this study aims to answer the question **whether innovations in alternative propulsion systems are induced by fuel prices.** Secondly, it intends to investigate how **innovations aimed at improving fuel efficiency of motor vehicles respond to changes in fuel prices**. Thirdly, the study aims to investigate **whether environment-friendly innovations directed to internal combustion engine are negatively affected by fuel prices.**

The contribution of this study to the existing body of literature on the induced innovation hypothesis is that the present paper aims to address several limitations of the previous studies. These limitations and the approaches to addressing them are mentioned in the following sub-section and are discussed greater in detail in the literature review.

1.2. Aim and scope

To answer the research questions the study intends to estimate the effect fuel prices have on several groups of innovations in the automotive sector. More specifically, **the paper aims to assess the price effect separately for the environment-related groups of innovations in the auto industry**: technologies devoted to *alternative propulsion* (*electric or hybrid)*, technologies directed to the improved *fuel-efficiency* and technologies related to emissions abatement in *internal combustion engine*.

Moreover, there are some reasons to expect that components of these groups can respond differently to price changes. In fact, each of the above-mentioned groups comprises of quite heterogeneous sub-groups of technologies (Haščič et al., 2009). It is likely, that due to the heterogeneity, the sub-groups of technologies have different diffusion patterns (OECD 2011: 118). One example is that electric propulsion is more radical change from technological point of view, than hybrid (OECD, 2011: 119). Therefore, it can be assumed that there is a difference in the way market forces affect innovative activity in electric and hybrid technologies. There are no sub-groups for *fuel-efficiency* group. As regards emissions abatement technologies related to ICE in vehicles, EPTI list distinguishes between two sub-groups: *integrated emissions control*, and *post-combustion emissions control.* Thus, this study aims to analyze separately *electric* and *hybrid* technologies, as well as *integrated* and *post-combustion* technologies to **examine how these more disaggregated groups of technologies are affected by price.**

It should be underlined that empirical testing of the induced innovation hypothesis in its pure form assumes that rate of innovation depends on the price of the production factor. Hence, the induced innovation hypothesis treats technological progress as exogenous, ignoring the role of knowledge itself on the propensity to innovate (Nordhaus, 1973). In other words, the effect current research efforts have on future progress of inventors is not taken into account. In his seminal paper Popp (2002) shows that failure to include knowledge base in the empirical estimation adversely effects the results. Therefore, Popp underlines that knowledge stock should be considered in empirical studies on induced innovation. More recent contributions to innovation literature stress that, apart from the knowledge stock of the inventor's country (as it is considered in Popp), the global knowledge flows have an impact on innovative activity (e.g. Verdolini & Galeotti, 2011; Dechezlepretre & Glachant, 2014; Dechezleprêtre et al., 2015). **This paper intends to exploit these recent developments by accounting for knowledge flows both from the inventor's country and from overseas.**

Initially studies on the directed technological change in general and studies on the auto industry in particular tended to focus on one country (e.g. the U.S. market in Popp, 2002; Crabb & Johnson, 2011; Jang & Du 2013). Only a few papers conduct cross-country analysis with tendency to focus on a set of the leading manufacturing countries (Haščič et al., 2009; Vollebergh, 2010). At the same time, in car industry a lot of patents are filed by smaller firms, which are not always located in major manufacturing countries (Aghion et al., 2014). Therefore, it makes sense to use a broader set of countries. Recently constructed databases, such as OECD Patent Database, allow expanding the dataset, while ensuring reliability of data. Hence, **this**

study aims to conduct analysis on a larger sample of countries. In particular, innovations in the OECD countries are considered.

Overall, the study intends to improve understanding of the role fuel price has on the innovations in the automobile industry. The contribution of the paper is as follows. First of all, the paper analyzes the effect prices have on fuel-efficient technologies and technologies directed to lower emissions output. Secondly, the paper examines how more disaggregated sub-groups (more homogeneous) respond to price changes to analyze whether prices affect these sub-groups in a different way. Thirdly, recent developments regarding the importance of knowledge stock are exploited. Finally, a broader dataset of countries is considered, than it is typical in the literature on technological change.

1.3. Outline of the thesis

The paper is organized as follows: Section 2 reviews previous theoretical and empirical research on the topic. A brief overview of the most significant regulations in the auto market, as well as a description of major technological developments is presented in Section 3. Section 4 is dedicated to the description of theoretical and empirical approach to the analysis. The limitations of the empirical strategy are also discussed. Section 5 provides the description of econometric analysis. The interpretation of estimation results is presented in Section 6. Finally, Section 7 concludes the paper.

2. Literature review

This section outlines a review of the literature related to the topic. Overall, although the literature assessing the role of price in directing technological change is vast, the empirical examination of the induced innovation hypothesis in relation to environment-friendly technologies is not very extensive. Initially empirical analysis was hampered by the lack of the appropriate data (Popp, 2002). More recent computerization of innovation-related data opened new doors to the empirical studies. As a matter of fact, earlier empirical papers tended to focus on a set of energy-efficient innovations, thus examining trends in environment-friendly patenting in the economy (e.g. Scherer, 1982; Jaffe & Palmer, 1997.). Lately there has been a trend of narrowing down the innovations to particular technological fields (e.g. Lee et al., 2011; Jang & Du, 2013, Dechezleprêtre et al., 2013). A few papers have studied automotive sector. Some of these papers are covered in this section. The limitations of the studies are discussed to underline how the present paper aims to contribute to the existing body of literature. Some additional comments on the field are presented in the end of this section.

2.1. Theoretical origins of induced innovation hypothesis

The term technological change is used to describe the state of economy when the increases in production output occur without any increase in the initial inputs (Löschel, 2002). In the broad sense, technological change is understood as a change in informational setting in the economy that allows extracting greater volume of output from the same volume of input (Thirtle & Ruttan, 1987: 12). This change occurs through the advancement in the products produced in the economy and the improvement of processes used in the production.

With given factor prices, the change in the proportion of inputs is known as the *direction* of technological change (Thirtle & Ruttan, 1987: 13). The technological change is *neutral* if the proportion of factors remains unchanged. When the proportion is affected, the technological change is viewed as *biased.* The factor use of which decreases is one that the bias is directed to. In other words, this factor determines the **direction of technological change**.

The strand of the literature on technological change analyzes factors that determine the direction of technological change. The notion that the direction of technological change is induced by the change in the relative prices of inputs and, more specifically, is directed away from the factor which becomes relatively more expensive is traditionally credited to Hicks (1932: 124). In other words, a rise in the price of one of the production factors fosters innovations directed to a lower use of this relatively more expensive factor. The rise in relative prices forces producers to economize on the expensive factor, therefore, the incentives to introduce innovation, allowing greater reliance on the cheaper input, arise. This proposition is known as *the induced innovation hypothesis*.

Being theorized by Hicks in 1932, the induced innovation hypothesis attracted greater attention in theoretical microeconomics after the classical papers by Ahmad (1966), Kamien and Schwartz (1968), and Binswanger (1974). The papers offered microeconomic formalization of induced innovation by modelling firm's response to change in factor prices in respect to firm's investment in R&D. Overall, these publications inspired theoretical discussion on the ways of modelling technological change.

2.2. Induced innovation and environment

Traditionally technological change and its direction have been considered in respect to labor and capital as primary factors of production. The majority of theoretical papers focus on the aggregate production function and explore how rise in wage affects the substitution of labor with capital (e.g. Salter, 1969; Binswanger, 1974).

However, later studies on the direction of technological change have expanded the set of factors under consideration beyond capital and labor. Thus, Newell et al. (1999) argue that technological change is intrinsically a product-level phenomenon, implying that it is not only the relative price of capital in respect to labor that may spur innovation, but also the relative price of goods. When costs of production rise for one good, firms get stronger incentives to develop an alternative product that incurs lower costs. Another novel approach introduced by Newell et al. (1999) is to examine the induced innovation hypothesis in respect to the costs for consumer, which makes a decision about the purchase considering costs of the final product. The classical theoretical papers (e.g. Ahmad, 1966; Binswanger, 1974) view technological change as the response of the producer to the changes in factor prices by investing in R&D. The approach used in Newell et al. (1999) rather focuses on the way producers respond to the changes in costs for consumers. In particular, technological change is modelled through a consumer's optimization problem, where a consumer makes the decision about the purchase based on the analysis of energy efficiency of the goods and their price. The idea behind this formulization is that the producer, in turn, decides in what stream of R&D to invest. Thus, energy price is viewed as the demand factor in the model.

In the empirical part of the study Newell et al. (1999) examine how product characteristics of a group of energy-consuming durable goods (e.g. air conditioners, water heaters, etc.) improve over time in response to energy price changes in the U.S. market. It is found that rising energy prices foster production and prompt commercialization of the improved models, as well as discourage spread of older models. The analysis of a change in product characteristics over time in relation to prices sheds light on the understanding of how prices affect energy-efficiency of the products. However, focus on specific parameters of products limits the conclusions drawn by the researchers to the results of innovation directed to certain products, rather than on the innovation process in the economy.

This limitation is overcome in the seminal paper by Popp (2002), who estimates the influence of price on the patenting behavior in environment-friendly innovations. Using the U.S. patent data from 1970 to 1994 Popp evaluates innovation activity in several technological fields in relation to energy prices. The prices are found to be a strong determinant of patenting in energy-efficient innovations. Popp concludes that environmental regulations (such as taxes on energy prices) can not only redirect innovation from polluting activities, but also stimulate progress in cleaner innovations.

An important contribution of Popp's study is that it shows that energy-efficient innovations are influenced not only by the demand factors (prices), but also by the supply side of innovation process. In particular, impact of the present base of scientific knowledge is estimated (so-called *knowledge stock*). Popp underlines that price gives incentives to innovate, but does not serve as a mechanism of innovation. In fact, the results reveal that knowledge stock has a significant positive effect on innovation. On the whole, the analysis indicates that prices (demand factor) foster patenting activity by rising the value of cleaner innovations, whereas available knowledge base (supply factor) lays foundation to make this innovations possible. It is emphasized that technological advancements, for which the chance of their realization is low, may be insensitive to price changes. However, extensive knowledge base may lay the groundwork for the technological progress, which can be further spurred by higher energy costs.

Popp claims that failure to account for knowledge stock underestimates the effect of prices. The argumentation is based on the following theoretical considerations. Induced innovation hypothesis in its classical form presumes that innovation rate is determined by changes in factor price. This formulation of the relationship between innovative activity and prices implies that technological progress is exogenous, and the existing base of scientific knowledge does not influence the innovative activity (Nordhaus, 1973). To put it differently, when technological progress is treated exogenously, the role of current research efforts on future innovative activity is not taken into consideration. Moreover, the importance of considering knowledge base among the determinants of innovations arises from the fact, that over time the quality of available knowledge deteriorates across technological groups at a different rate (Popp, 2002). Some ideas become outdated, some developments become obsolete. In fact, Popp shows that there are diminishing returns in the research output of some sectors, implying that over time the productivity of the existing research output decreases for future inventors. Therefore, the model that does not account for knowledge stock, fails to capture the difference in the relevance of previous developments in the field.

Another supply-side factor considered in Popp's study is public R&D. The factor is found to have no significant effect on energy-efficient innovation. The interpretation of this result is based in the argument that public expenditure on R&D in environmentally-friendly technologies may crowd out private investment.

All in all, Popp's seminal work laid the empirical and theoretical foundations for the environment-related studies in the field of the induced innovation analysis. The findings have inspired some empirical attempts to find the evidence for the hypothesis using a broader set of countries, focusing on other technologies, and improving methodological approach.

Thus, Verdolini and Galeotti (2011) examine how both supply and demand factors affect energy-saving innovation across 38 countries. The authors provide empirical evidence in support of the induced innovation hypothesis, demonstrating that patenting in energy-efficient technologies is positively related with energy prices. It is also found that supply-side factors (knowledge stock) foster innovations.

The paper broadens the concept of knowledge stock to account for knowledge flow from overseas. More specifically, the paper incorporates the concept of knowledge spillovers, which has received greater attention in innovation literature recently (Acemoglu et al., 2012). Knowledge spillover is the amount of knowledge generated by an agent, which becomes available to public (Kaiser, 2002). On the one hand, the fact that one's ideas become public and can be appropriated by others means that returns to the original idea decrease. On the other hand, availability of private knowledge to public may engender more innovations (Pizer & Popp, 2008).

In their study Verdolini and Galeotti (2011) presume that inventors in one country can benefit from the existing knowledge base of other countries, apart from knowledge base of their own country. The motivation behind this assumption is based on the increasing role of globalization in the worldwide trade and production. The paper treats the amount of external knowledge available to inventors in one country as the amount of knowledge generated overseas multiplied by the probability that knowledge crosses the border. The authors evaluate the factors driving knowledge diffusion and find that greater geographical and technological distances hinder knowledge flow.

Jang and Du (2013) analyze innovative activity of U.S. firms in biofuel industry and find that price of crude oil, as well as government R&D expenditure and existing knowledge stock spur patenting in ethanol-related technologies. Freitas and Kaneko (2012) document the stimulating effect of oil price on ethanol-related technologies. Positive effect of crude oil price on innovations directed to development of solar photovoltaic modules is reported by Peters et al. (2012).

2.3. Technological change in auto industry

2.3.1. Induced innovation in auto industry

There is some research on the topic devoted to the auto industry. Using a sample of patents granted in the U.S. between 1980 and 1999, Crabb and Johnson (2010) analyze the effect of monthly price change on energy-efficient innovations in the auto sector. Crabb and Johnson define energy-efficient innovations as those directed to better fuel-efficiency together with technologies in electric and hybrid propulsion. The analysis provides empirical support for the induced innovation hypothesis. In addition, dummy variables for the environmental standards launched in the U.S. (US CAFE) are used. The study finds no evidence about their influence on innovative activity in the sector.

The paper focuses on monthly data to account for monthly variation in price. However, the dependent variable which is based on patent counts is subject to time lag. In particular, usually the date of invention differs from the date of filing the application for the patent (OECD, 2009: 61). It is a standard practice in innovation literature to use the date of application to date a patent (Popp, 2002; Verdolini & Galeotti, 2011; Jang & Du, 2013), as it is the date closest to the invention. However, when the patents are dated on yearly basis, the inaccuracy of timeliness is partly offset due to the length of period. With more frequent data more inaccuracies may arise[1].

A few considerations reveal opportunities for extending the research design used by Crabb and Johnson (2010). First, in their study technologies directed at higher fuel efficiency and technologies in alternative propulsion are considered as one group of energy-efficient innovations with the latter representing only a small share of all the observations. In fact, due to the time limit the sample does not account for more recent progress in alternative fuel vehicles. Moreover, those patents which are included are those filed by the automotive industry in the U.S. Consideration of more recent period of time allows taking latest developments in to account. Furthermore, a broader set of countries in the sample allows not only to control for greater variety of producers, but also to have more observations in the resulting sample. Having more observations allows running regressions dividing energy-efficient innovations in several technological sub-groups.

Aghion et al. (2014) explore firm-level innovating activity in the automotive sector by distinguishing between 'clean' and 'dirty' technologies. The latter comprises innovations in

[1] If the invention took place on 28th of August in 1998, there are still 4 months in which patent may be applied for so as the factual year of invention (1998) will correspond with the nominal (patent application date) and not with the next one. Whereas on monthly basis, already in four days the nominal month and the factual month of invention will differ, as long as patent is not applied for in the same date as the invention took place.

hybrid and electric technologies, the former includes innovations specific to ICE. The focus of the paper is on the role of path-dependence in redirecting technological change in the industry. In particular, past history of firm's innovation is examined as a determinant of patenting activity. Path dependence in innovating activity implies that the decision about investing in innovation today depends on the innovations generated by the firm in the past.

The study presents a microeconomic model in which an auto producer makes a decision about firm's R&D evaluating expected returns and external factors. The model predicts that higher fuel prices increase investment in 'clean' R&D and, therefore, spur innovation in 'clean' technologies. The effect of prices on 'dirty' innovations is the opposite: rise in fuel prices leads to a decrease in 'dirty' R&D, thus resulting in lower amount of 'dirty' innovations. The intuition behind this prediction is as follows. Consumers treat 'clean' and 'dirty' cars as substitutes. When fuel for widely used 'dirty' vehicles becomes more expensive, consumers switch to 'clean' cars. Consequently, the market share for 'clean' vehicles grows, whereas for 'dirty' it declines. Therefore, returns on 'clean' innovations rise and returns on 'dirty' innovations fall. Thus, higher fuel price encourages 'clean' and discourages 'dirty' innovations.

Another key prediction of this model is that if in firm's history share of 'clean' innovations is greater, than of 'dirty' ones, the firm is more likely to continue innovating in 'clean' technologies. The same logic holds for 'dirty' innovations. The intuition of this statement is that profitability of one group of innovations is higher if firm has already put some efforts in developing the technology (already has a greater share of this type of technologies in the innovation portfolio). For instance, if a firm has already innovated a lot in dirty innovation, a switch to cleaner technology may require hiring new researchers, investing in new types of capital, thus incurring higher costs.

It is worth noting, that these theoretical predictions are consistent with the considerations made by Acemoglu et al. (2012). In their paper authors introduce a growth model with endogenous technical change. The model shows that in laisses faire economy producers will always prefer investing in 'dirty' technologies over 'clean', as long as the 'dirty' and 'clean' inputs are strong substitutes. The intuition is that 'dirty' technologies are initially more advanced, as they have been developed earlier. In other words, there is a gap between 'clean' and 'dirty' technologies and there is a need for 'clean' technologies to catch up. This gap affects profitability related to the development of the technologies, making 'dirty' ones more attractive, as they require less technological effort and time, while discouraging research directed towards 'clean' technologies. At the same time, the paper concludes that the transition to 'clean' technologies may be reinforced by policy measures (research subsidies and carbon taxes).

Aghion et al. (2014) examine the above mentioned theoretical predictions empirically and find supportive evidence for both of them. It is found that 'clean' innovations are induced by high fuel prices, while 'dirty' technologies are discouraged by increases in price. The fact that the second prediction also gets empirical support means that fuel taxes are not enough for redirecting technological change in the industry. Given that the stock of innovators in 'dirty' technologies is higher than in 'clean', the reported path-dependence of innovation choice signifies that without a drastic intervention, the prevalence of 'dirty' technologies should be expected. The authors emphasize the need for action. The simulations conducted in the paper reveal that 40% increase in fuel price would assist 'clean' technologies in overtaking 'dirty' ones within 15 years (Aghion et al., 2014: 32). Interestingly, the authors also show that firms that are more exposed to 'clean' innovations are more likely to generated more 'clean' patents. The same holds for 'dirty' patents. By being exposed the authors mean the spillover effect. Greater exposure to a technology is understood as greater spillover effect. Thus, the paper points out that is not only firm's own history of innovation that matters, but also the history of other producers.

Aghion et al. (2014) recognize the limitation of their theoretical assumption that the substantial improvement in energy efficiency can be achieved only by the non-combustion vehicles. The present study aims to elaborate on this limitation, by separately considering efficiency-oriented technologies in ICE and non-combustion innovations. Moreover, as it was already mentioned, differing patterns of market diffusion for the alternative propulsion may signify difference in the determinants of these technologies. Therefore, apart from examining 'clean' innovations, the present paper separates electric and hybrid propulsion.

Haščič et al. (2009) analyze patenting behavior in automotive industry across the developed countries in respect to the emission-control technologies used in the ICE-based vehicles. The study compares the determinants of innovation in a set of *integrated technologies* (crankcase emissions control, air-fuel ratio controller, etc.) with innovation in *post-combustion devices* (catalytic converters and regenerators). Analysis reveals that fuel prices and policy regulations affect the technologies in a different way. In particular, it is shown that fuel price has a significant positive effect on innovations in *integrated technologies,* whereas it is found to be insignificant for *post-combustion devices.* At the same time, estimation reveals that policy standards affect *post-combustion devices,* implying that regulation is a strong determinant of innovation in this technological group. Whereas for *integrated technologies* only a few measures are significant. The authors claim that these differences appear, on the grounds that different parties benefit from these types of technological improvements, and, therefore, different parties have incentives for their development and implementation. More specifically, it is argued that apart from reducing emission output *integrated technologies* reduce maintenance costs and can increase fuel efficiency, thus bringing both public and private benefits. While post-combustion devices only prevent the release of pollutants, thus generating only public benefit.

Also the approach to research design in Haščič et al. (2009) is close to the part of the present paper, where environment-friendly technologies specific to ICE are examined, clear distinctions should be highlighted. Firstly, the set of technologies considered by Haščič et al. (2009) contains only a subset of technologies analyzed in the present paper[2]. Secondly, the research design of the reviewed study does not take into consideration the effect of previous research in the area of ICE technologies on patenting behavior. Thus, the model does not include the effect of previously obtained knowledge in the area. Neither knowledge stock, nor knowledge spillovers are accounted for. The present study takes these notions into consideration.

A broader set of innovations directed at ICE is explored in the paper by Vollebergh (2010). The focus of the study is on the impact of policy standards on the four categories of innovations in combustion engine. In particular, the following groups of patents are considered: directed at emissions abatement, at the substitution of emission-intensive input for emission-extensive, at the replacement of 'dirty' inputs by 'clean' and at the fuel efficiency. The paper examines effects of policies using numerical expression of standards in units (e.g. the amount of allowed NOx emissions in grams per kilometer) and finds that various policy measures and environmental standards affect the patenting activity in each of the categories to the different extent. Apart from policy measures, petrol prices are considered. The estimation reveals that petrol price is negatively correlated with the three groups of innovation. This result partly contradicts with the findings in Haščič et al. (2009). Vollebergh (2010) argues that the negative relationship between fuel price and innovations in emissions abatement arises because after an upsurge of fuel prices consumers are likely to reduce their driving or even switch to more fuel-efficient vehicles. This behavior results in at least some decrease in emissions and, therefore, reduces incentives of inventors to target emissions abatement.

In the model considered by Vollebergh (2010) prices are taken for the current period, whereas the majority of similar studies usually lag prices (Haščič et al., 2009; Verdolini & Galeotti, 2011; Aghion et al., 2014). Lags are used in assumption that it takes time for inventors to generate ideas in response to changes of economic conditions. Thus, apart from different grouping of patents, the present study differs in relation to measuring price. Additionally, while focus of

[2] While choice of technologies in Haščič et al. (2009) was also motivated by environmental reasons, this list was constructed before the list of technologies with promising environmental impact was published by EPTI (OECD, 2011). The list is being constantly updated, therefore, more technologies could have been added since the list by Haščič was created. For instance, Haščič et al. (2009) do not include such technologies as *Monitoring devices for exhaust-gas treatment, Testing of IC by monitoring exhaust gases, etc.*

Vollebergh (2010) is on the effect of the real restrictions on the allowed amount of emissions, the present study focuses on fuel price, controlling for policy standards with the help of dummy variables.

2.3.2. Other frameworks for auto industry analysis

At the same time, while examining innovating activity in auto sector, some papers do not take into account the price effect. Thus, the focus of paper by Lee et al. (2011) is on the industry-level regulation of emission standards. Using data on patenting in auto emission control technologies in the U.S. between 1970 and 1998, the authors find out that regulations induce innovative activity of both automakers and their suppliers. Dechezleprêtre et al. (2015) add that apart from policy measures introduced in the inventor's country, innovative activity in the auto sector depends on the policy measures taken abroad. The analysis suggests that due to the global character of the automobile market, increases in regulation stringency occurring in one country are also likely to affect innovative incentives in the other countries as well.

Finally, this paper is also related to the strand of literature that investigates the demand for automobiles as a function of fuel prices. For instance, Busse et al. (2009) show that increase in prices leads to a decrease in demand for motor vehicles. Similar result is found by Alcott and Wozny (2014). Overall, even though the estimated elasticity of demand differs in the studies, it is commonly accepted that demand for automobiles is sensitive to the prices of fuel.

2.4. Alternative approaches to examining technological change

It is worth mentioning that literature on technological change is not limited to the examining the role of price in accordance with the induced innovation hypothesis. This paper is devoted to the induced innovation hypothesis, therefore, application of alternative theoretical frameworks is out of scope of this study. A few examples of recent contributions to the field of directed technological change are the papers by Acemoglu (2002) and Fouquet (2010). An important consideration made by Acemoglu (2002) is that apart from the effect of factor prices, direction of technical change can be affected by another competing force – market size. Market size effect implies that once the technology is introduced to the market, it becomes easier for other producers to implement it, as relevant knowledge about the technology spreads. Price effect and market size effect are considered as competing, as the first one favors technologies directed at scarce factor of production, while the second facilitates innovations directed at abundant factors. The magnitude of the effects is argued to depend on the substitution between the factors. Fouquet (2010) argues that technological change is driven by opportunities for less costly and more efficient production process. In particular, it is emphasized that economic conditions allowing creation of niche markets define the direction of change. These theoretical consideration are out of scope of this study.

3. Overview of the automotive sector

This section briefly outlines major developments in the regulation of the auto industry and describes technological evolution in the automobile production.

3.1. Overview of regulation

Since mid-20th the automobile sector has experienced dramatic changes in the regulation standards worldwide. In 1960s due to the escalated environmental concerns first environmental standards on the national level were introduced by the U.S., EU and Japan. These regulations were not very strict, requiring a few modifications to the engine design (Perkins & Neumayer, 2012). Some tightening of the policy stringency was caused by the concerns about efficiency of motor vehicles, which soared rapidly after the oil crisis of 1973.

In late 1970s the U.S. Corporate Average Fuel Economy Standards (US CAFE) promoted substitution of carburetors with electronically-controlled fuel injections both for environmental and energy-saving reasons (OECD, 2004: 30). More technologically demanding regulations calling for more drastic changes in the engine design were introduced by the U.S. in 1987 (Tier 0) and the EU in 1992 (Euro 1), and soon were adopted by a range of other countries (Perkins & Neumayer, 2012).

The following rise in stringency of standards in the U.S. was introduced in 1994 (Tier 1) and then in 2003 (Tier 2). Euro 2 in the EU was put into practice in 1996, followed by Euro 3 in 2000, Euro 4 two in 2005 and Euro 5 in 2009 (Perkins & Neumayer, 2012). Both American and European standards targeted the allowed amount of tailpipe emissions: carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbon compounds (HCs). In addition, the standards for the amount of particulate matter (PM) released by vehicles started to gain force from 1994 in the U.S. and EU. As compared to 1970s the allowed amount of CO, HC and NOx tailpipe emissions decreased by around 95% (Haščič et al., 2009).

While in the U.S. and EU changes in policy standards were relatively gradual with more stringent requirements appearing after some lags, in Japan the regulation of automotive sector was more radical. After the first requirements for tailpipe emissions introduced in late 1970s, the following drastic changes took place around 2000, when the allowed amount of emissions was decreased by around 94% (Haščič et al., 2009).

3.2. Overview of technological developments

3.2.1. <u>ICE-related developments</u>

Ability to comply with regulative changes required technological enhancements of vehicle design. Both rising environmental standards and surging fuel prices raised concerns about improving fuel-efficiency among auto makers (OECD, 2011: 89). From the technological aspect the first attempts of improving fuel efficiency of vehicles were aimed at redesigning ICE. In particular, before 1970s fuel efficiency of motor vehicles was to a larger extent affected by carburetor-related improvements (OECD, 2004: 28).

In response to the tightening standards in mid-1970s auto makers introduced catalytic converters, which allowed complying with stricter emission requirements (OECD, 2004: 28). Subsequent considerable improvements in fuel efficiency came into place in 1990s, when developments the direct injection system were introduced. Later the efforts of remodeling engine were complemented by changes directed towards other parts of vehicles (lower friction of surface material, arrangements to the braking system, etc.). Although the introduced technological improvements of non-engine characteristics led to lower consumption of fuel, the improvements were incremental (OECD, 2011: 86). At the same time, it should be noted that developments in engine design were not always driven by environmental motives. Greater engine power, higher vehicle safety or better design are just some of the examples that can be the objectives of R&D.

Furthermore, it should be mentioned, that not all the measures directed towards reduction of emissions in motor vehicles are consistent with increase in energy efficiency. Some of the emission-control developments lead to improvement in fuel efficiency, while others can increase fuel consumption or emissions of another pollutant (Haščič et al., 2009). On the other hand, achievement of fuel economy goals, can result in increased emissions. Thus, emissions control and improved efficiency create a need for trade-off in policy making.

Since late 1990s innovations of a more radical nature have been actively developing in the automotive industry. In general, these more radical innovations are aimed at improving fuel efficiency, decreasing greenhouse gas emissions and local air pollution (OECD, 2011: 86). A brief description of more radical technologies in auto making follows.

3.2.2. Alternative technologies

Overall, ICE transforms chemical energy into energy by combusting fuel. Fuels which contain lower amount of carbon and higher amount of hydrogen (such as hydrogen itself, natural gas or ethanol) have a potential of lessening carbon dioxide emissions (OECD, 2011: 89). There is a variety of fuels which can be used instead of gasoline or diesel. Ethanol, methanol, liquefied petroleum gas and biodiesel are some of the examples of the alternative fuels which after some technological adjustments can be used in conventional ICE vehicles. In general, the downside of using the alternative fuels is associated with either health concerns or increased emissions (OECD, 2004: 12).

More radical approach to reducing automotive emissions is implementation of alternative propulsion systems. Alternative propulsion systems can be fuelled by electricity, hydrogen or hydrocarbon fuels (Figure 1).

Figure 1. Classification of motor vehicles

<table>
<tr><td colspan="3" rowspan="2"></td><td colspan="3">PROPULSION SYSTEM USED</td></tr>
<tr><td>Internal combustion engine</td><td>Hybrid propulsion</td><td>Electric propulsion</td></tr>
<tr><td rowspan="4">FUEL USED</td><td>Liquid</td><td>Hydrocarbons</td><td>Conventional gasoline/diesel vehicles</td><td rowspan="3">Hybrid electric vehicle</td><td rowspan="3">Fuel-cell electric vehicle</td></tr>
<tr><td rowspan="2">Gaseous</td><td>Hydrocarbons</td><td>Liquefied natural gas or Liquefied petrol gas vehicle</td></tr>
<tr><td>Hydrogen</td><td>Hydrogen vehicle</td></tr>
<tr><td colspan="2">Grid electricity (external source)</td><td>-</td><td>Plug-in hybrid electric vehicle</td><td>All-electric vehicles</td></tr>
</table>

Source: adopted from Haščič et al. (2009) and https://www.fueleconomy.gov/feg/evtech.shtml

Electric vehicles derive mechanical energy from electric energy, which for all-electric vehicles is drawn from battery and for fuel-cell electric vehicles is converted from chemical energy of fuel. All-electric vehicles are considered as the most promising, as they generate no carbon emissions (OECD, 2004: 12). Environmental impact of fuel-cell vehicles depends on the fuel used, but with hydrogen only water is generated during the energy conversion, producing no emissions (OECD, 2004: 13). Hybrid vehicles combine two propulsion systems. Most often ICE is used a primary power source to support performance of the electric generator, ensuring high conversion efficiency and substantially lower emission output than conventional cars (OECD, 2011: 90).

The major problem of the alternative propulsion systems so far is the weakness of currently available storage systems and high costs of the production (IEA, 2013: 3). In general, adoption of the alternative propulsion systems in car making is expected to yield improved fuel efficiency, as well as a decrease in exhaust emissions caused by motor vehicles (OECD, 2004: 7). However, as it was underlined the overall environmental effect of using electric or hybrid cars depends on the way fuels for them are generated.

4. Methodology

This section explores theoretical and empirical approach to testing the induced innovation hypothesis for the auto sector. First, theoretical foundation of the study is discussed. Next, the empirical model is described revealing how the theoretical considerations are transformed into the empirical strategy. Next, the data are presented.

4.1. Theoretical approach

This paper examines the effect of changes in fuel prices on environment-friendly technologies in the auto sector. Both technologies motivated by fuel efficiency reasons and by emissions control are analyzed. The present study draws primarily on the seminal work by Popp (2002), which offers both theoretical and empirical developments to the interpretation of the induced innovation literature in the context of environmental innovation. In addition, the study makes use of the work by Aghion et al. (2014), which provides some insights in the approach to estimating price effect in the automobile sector.

4.1.1. Interpretation of the induced innovation hypothesis

The induced innovation hypothesis posits that a rise in relative price of one of the production factors stimulates innovations directed towards the reduced use of this more expensive factor (Hicks 1932: 124). In application to the environment-friendly innovations, the induced innovation hypothesis requires distinct interpretation. A brief interpretation was mentioned in the introduction, the more detailed interpretation follows. First of all, since the contribution made by Newell et al. (1999) in the context of environment-friendly innovation '*factor*' is *energy* (e.g. Popp, 2002; Acemoglu et al., 2009; Crabb & Johnson, 2010). Accordingly, in the context of the auto industry the focus is on the *price of fuel,* and in the context of the directed technological change, on the *price of fossil fuel* (based on oil). In the empirical estimation lagged prices are used in assumption that innovation needs some time to be generated after prices start changing (Crabb & Johnson, 2010). Next, '*innovations*' directed towards the reduced use of a more expensive factor are *energy-saving innovations*. From technological perspective, lower use of the fuel can be achieved either by redesign of motor vehicles with conventional ICE or by implementation of alternative propulsion in vehicles[3].

Redesign of ICE and implementation of alternative propulsion system differ not only in the extent to which they lower usage of fossil fuels, but also in the requirements they raise for vehicle adjustment. In particular, while redesign of ICE implies incremental changes in the existing parts of motor vehicles (such as arrangements to braking system), alternative propulsion requires not only greater changes to the vehicle design, but also to the surrounding infrastructure. Moreover, types of propulsion systems differ in their implementation. While both electric and hybrid vehicles require development of the on-board storage systems, the cost of this development for hybrid vehicles depends on the extent to which a vehicle relies on the alternative fuel, whereas electric cars bear the full cost (OECD, 2004: 76). These differences allow viewing electric technologies as more radical than hybrid (Haščič & Johnstone, 2011). These considerations motivate to examine the technologies separately when testing the induced innovation hypothesis.

[3] Such non-technological aspects as the driving skills or the degree of congestion are out of the scope of the study.

4.1.2. On measurement of policy stringency

The great attention the literature on technological change pays to prices stem from the fact that fuel price can serve as a tool used by policymakers. In fact, primary goals of fuel taxation may not necessarily be to mitigate externalities, but rather to raise revenue. Nevertheless, taxes on fuel are still considered as implicit regulatory instrument, as they lead to an increase in price (Vollebergh, 2010).

In general, price is not the only mechanism of environmental policy. There is an on-going debate on which policy tools serve more efficiently for environmental goals. For instance, Fisher and Newell (2008) claim that the most efficient policy in rising innovative incentives is direct pricing of emissions. Performance standards and fossil fuel taxes are found less efficient. Research subsidies are shown to be the least effective. Lee et al. (2007) compare policies that force implementation of certain technological improvements with policies that set performance targets with no requirement on the way of achieving them. The comparison reveals that the latter stimulate innovative activity to a greater extent than the former.

Overall, for a cross-country study the direct comparison of policy measures becomes more complicated, as countries differ considerably in the set of measures they implement, as well as in the practices of reporting the policy incentives. For instance, the pollution abatement expenditure is often used to approximate for the stringency of policies, however, the measure of expenditure is based on the surveys, methodology of which differs across countries thus hampering comparability (Dechezleprêtre et al., 2015). Overall, cross-country studies tend to focus on public R&D expenditure to approximate the policy incentives, as this measure is widely available and is believed to be comparable across countries (Verdolini & Galeotti, 2011). In addition, it is common for cross-country studies on the auto sector to consider the stringency standards introduced in the regions where the major producers are located. For instance, while examining the sample of all the OECD countries, Haščič et al. (2009) focus on the emission regulations in the U.S., EU and Japan due to the significance of the U.S., Japanese and European markets for car makers.

There is, in fact, both empirical and theoretical motivation for this. Vogel (1997) argues that economic globalization can engender tendency of environmental policy standards to ascent up to the levels established in high-regulating countries (known in literature as 'California effect'). The ascent of policy standards may take place if exporters try to adjust to the standards adopted by the destination countries, so as not to be rejected an access to the market on the grounds of non-compliant imports. In turn, adoption of more stringent standards makes production more costly for the exporter. Therefore, so as not to lose advantage on domestic markets large producers may try to lobby their domestic governments to introduce more stringent polices at home.

Perkins and Neumayer (2012) find the empirical support for the existence of a cross-border California effect in the auto market. The study reveals that cross-border trade with countries that have higher environmental standards results in more stringent domestic environmental standards in the economies with initially lower environmental regulation. A similar effect is found to be driven by cross-border investment. The study emphasizes that the international character of trade and investment in the automobile industry creates strong incentives for car makers to reconcile product characteristics of vehicles designated to different markets. As a matter of fact, the authors mention that the majority of the developing countries have relied on the environment regulations adopted in the EU countries as the basis for the domestic environment standards.

This theoretical consideration complemented by the robust empirical evidence found for the automotive sector justifies an approximation of policy regulations by focusing on the countries with more stringent policies. Hence, the data on regulations adopted by the U.S., EU and Japan are used to control for increases in policy stringency for the whole sample of countries.

4.1.3. Knowledge stock and spillovers

As it was highlighted in the literature review, recent studies on technological change tend to account for the effect of the existing knowledge base. As it is shown by Verdolini and Galeotti (2011) countries benefit not only from the domestic knowledge bases, but also from the knowledge flows from abroad. Aghion et al. (2014) add empirical evidence supporting this statement for the auto industry.

Even though knowledge spillover effect has long been debated in both theoretical and empirical literature on innovation, the analysis of spillover from overseas on the country-level has been introduced only recently (Verdolini & Galeotti, 2011). Evidently, knowledge stock is not observed, therefore, approach to its estimation is built on a set of theoretical assumptions. Overall, the concept of measuring knowledge spillovers is based on summation of the knowledge stock, which could be obtained from other agents (firms, regions or countries). Knowledge stocks of other agents are usually assigned weights to account for the probability of knowledge flow to become accessible.

To assign weights for knowledge stocks Verdolini and Galeotti (2011) build a model to estimate probability that knowledge crosses the border as a function of geographical, cultural and technological proximity. Aghion et al. (2014) presume that the share of knowledge the firm gains from the knowledge stock of a particular foreign country depends on the amount of inventors this firm has in that particular country. Alternatively, weights can be approximated by import-based measures or the volume of foreign direct investment (Pizer & Popp, 2008). In fact, having compared several measures of weights for knowledge spillovers, Kaiser (2002) concludes that Jaffe's index of technological proximity, as well as the direct measures obtained from surveys work reasonably well. At the same time, distance-based measures are not recommended to be used. This paper draws on these conclusions and accounts for knowledge spillovers using measure of weights based on the Jaffe's index of technological proximity (see Appendix Note 1).

4.2. Empirical approach

4.2.1. Model

Tests of innovation hypothesis are typically performed using econometric models that examine innovations as a function of factor price, variables approximating the available knowledge base and variables representing innovating activity in the country. Combining empirical strategies discussed by Popp (2002), Crabb and Johnson (2010) and Aghion et al. (2014) this paper estimates the following model:

$$ln\left({PAT_{z,it}}/{TOTPAT_{it}}\right) = \alpha_z + \beta_{z,1} lnP_{it-1} + \beta_{z,2} lnK_{it-1} + \beta_{z,3} lnSPILL_{it-1} + \beta_{z,X} X_{it} + \upsilon_{z,it} \quad (1)$$

Index i denotes countries, t - years. Index z stands for the type of technology under consideration: *Alternative* (alternative propulsion), *Fuel efficiency* (directed at improved fuel efficiency of vehicles) or *Conventional* (specific to ICE). Thus, at the first stage the model is estimated for $z \in$ {*Alternative*, *Fuel efficiency, Conventional*}. At the second stage, *Alternative* and *Conventional* groups were disaggregated to construct more technologically close sub-groups. In particular, at the second stage $z \in$ {*Electric, Hybrid; Integrated, Post-combustion*}. These groups are discussed in detail in the part devoted to data description (4.3.1).

The dependent variable represents innovative activity. In this study innovative activity is approximated by patent count. The choice of innovation measure is justified in the section devoted to data description (4.3.1). The measure is constructed as a logarithm of the share of patents in technology z ($PAT_{z,it}$) in the total amount patents applied for in the corresponding year t in the corresponding country i ($TOTPAT_{it}$). It is argued that the advantage of the percentage over the simple count data is that it accounts for the exogenous changes in patenting activity over time (Popp, 2002). Moreover, focus on the percentage makes cross-country comparison more meaningful, as it controls for changes that affect growth in patenting activity across countries (Crabb & Johnson, 2010).

Variable lnP_{it-1} denotes the logarithm of lagged fuel prices in country *i*. In fact, both lag *t-1* and lag *t-2* are considered. The induced innovation hypothesis predicts that when factor prices go up, innovations are directed at lower use of the factor that rises in price. Thus, in accordance with the hypothesis, in application to model (1) the positive sign of lnP_{it-1} is expected. The model suggested by Aghion et al. (2014) adds that technologies directed to ICE are inversely related to the fuel price. Thus, a negative sign of fuel price for specifications with ICE technologies would provide support for this prediction.

The history of country's innovation in motor vehicle technologies is captured by K_{it-1}. Knowledge spillovers from auto sector are denoted as $SPILL_{it-1}$. More detailed description of these measure is discussed below.

The vector of control variables is denoted as X_{it}. Control variables include public R&D in transport sector. In addition, some specifications of the model include dummy variables for policy measures introduced in the largest auto markets (the U.S., EU, and Japan). Public R&D is expected to have a positive influence on patenting activity, as it is supposed to support producers (Fisher & Newell, 2008). On the other hand, investment in R&D financed by government can crowd out private investment (Pizer & Popp, 2008). Therefore, if private investments are discouraged by public R&D, negative coefficient or even insignificant can occur. Finally, $v_{z,it}$ is the error term.

Patent stock is commonly calculated using the perpetual inventory method (see, for instance, Verdolini & Galeotti, 2011, Jang & Du, 2013, Aghion et al., 2014). The idea of the perpetual inventory method is that current stock is measured as a cumulative sum of previous additions to the stock minus the depreciation of the stock. In application to the knowledge stock the perpetual inventory method implies that current knowledge stock is a cumulative sum of the patent counts (patents represent the innovation capital) with respect to the depreciation of knowledge (obsolescence of innovations). Thus, as it is standard in innovation literature, knowledge stock $\mathrm{K_{it}}$ or country i in the period t is calculated in the following way:

$$K_{it} = (1 - \delta)K_{it-1} + PAT_{it},$$

where δ is the rate of depreciation and PAT_{it} is the amount of patents applied for in the corresponding year. Rate of depreciation for innovation capital is usually considered as ranging from 10 to 20%. This study uses 20% as it is the rate commonly used for innovation in manufacturing (see, for instance, Dechezleprêtre et al., 2015). The initial knowledge stock K_{i0} is calculated as the average patent count for the country over the period under consideration. Positive sign of knowledge stock would indicate that patenting activity benefits from the existing knowledge base (Popp, 2002). Positive sign would imply that the greater is the volume of relevant ideas available to the researchers in one country, the greater is the amount of ideas that can be generated. Popp adds that some technological fields tend to experience diminishing returns for the research output. Diminishing returns imply that with time it becomes more challenging to generate new ideas and to make new discoveries. Consequently, to generate innovations, greater investment is needed. Diminishing returns can arise, when knowledge in the field is well established and already extensive. Thus, further increase in the existing knowledge base can have an adverse effect on the growth of patenting activity in the field.

Knowledge spillovers from overseas are calculated as follows:

$$SPILL_{it} = \sum_{j \neq i} w_{i,j} K_{jt},$$

where w_{jt} signifies weights of knowledge stock. The stock is weighted in accordance with country's technological proximity index developed by Jaffe (1986). The description of the index can be found in the Appendix (Note 1). Overall, the measure summarizes knowledge stocks available from other countries in assumption that knowledge flow is facilitated by the technological proximity. According to this assumption, knowledge flows with higher likelihood for countries with more similar patent portfolios. Positive sign of the spillover effect would signify the favorable impact of knowledge flows: innovation is stimulated by the knowledge accessible from foreign inventors. Alternatively, negative sign occurs if the spillover leads to the leakage of commercial secrets, reducing the returns to the original owner of the idea (Kaiser, 2002).

In general, it should be underlined, that knowledge stock is in principle an unobservable concept, therefore, any approach to measuring it is just an approximation. Therefore, all the estimation results derived for this measure should not be interpreted in terms of magnitude, but rather in terms of direction of influence (negative or positive impact).

It should be mentioned that knowledge stock and spillover measures were constructed for all the groups (as well as subgroups) of patents. Initial motivation was to combine some of the measures in various specifications. For instance, the model considered by Aghion et al. (2014) includes knowledge stocks from several sources ('clean' and 'dirty' stocks) to draw conclusions about the path dependence (depending on signs of the coefficients it can be deduced what knowledge stock fosters each type of innovations). However, the constructed measures were highly correlated (above 85%), therefore, caused severe multicollinearity problems. Hence, drawing on the conclusion made by Aghion et al. (2014) that both 'clean' and 'dirty' innovations depend from all the types of knowledge stocks, knowledge stock in estimation is based on the sum of the auto patents.

4.2.2. Estimation strategy

In assumption that predictor (fuel price) is not correlated with the error term, estimates of the pooled OLS model are consistent. However, for panel data random-effects estimators are more efficient. At the same time, if predictor is correlated with the error term, neither OLS, nor random-effects provide consistent estimates. Hence, the following form of the error term can be assumed:

$$v_{it} = \varphi_i + \varepsilon_{it},$$

where country effects are denoted by variable φ_i and ε_{it} signifies the error term. This representation allows assuming that the predictor is not correlated with the term ε_{it}, while the correlation between the predictor and error term v_{it} arises from the correlation with time-invariant effects (φ_i). Such an assumption is compliant with fixed-effects model. In fixed-effects model individual effects, which are unique to the entities under consideration (countries), are assumed to be correlated with the outcome variable. Fixed-effects estimators eliminate these individual effects. All in all, both fixed-effects and random-effects models are estimated and tests are conducted to choose between the models.

4.3. Data

4.3.1. Patents as a measure of innovation

Measurement of innovations is a long lasting debate in innovation literature (Smith, 2006). In principle, innovation is a process that can hardly be measured in one unified way, therefore, empirical literature tends to focus on certain measures acknowledging their shortcomings. As it is common in literature on technological change, this paper uses patent count measure.

Patent count as a measure of innovation has several limitations. First of all, patents measure inventions rather than innovation; invention represents an idea, while innovation is its implementation (Smith, 2006). Furthermore, not all the inventions are patented and not all the innovations are suitable for patenting. For certain types of innovations alternative methods of protection (such as lead time, secrecy, etc.) may serve better (OCED, 2009: 44). Secondly, patents often significantly vary in their value. While some patents represent ideas that bring prominent improvements to society, some may have no industrial application at all or may not even be implemented after being granted. Thirdly, it is well-known that the propensity to patent ideas differs across sectors, as well as across countries (Levin et al., 1987). Aspects of law enforcement, the application fees, bureaucracy may all affect the propensity of inventors to protect their ideas by patents, making it difficult to compare patenting activity across countries. Finally, patent application hardly ever takes place at the same time the invention occurred.

Therefore, there is a bias in dating innovations approximated by patents: most often the date of application is later than the date of invention itself.

At the same time, patents as indicator of innovative activity have strong advantages. Firstly, patent count data are accessible on technologically disaggregated level, so that it is possible to distinguish between the different technological areas. In principle, data of similar detail level for the alternative measures of innovation (e.g. R&D expenditure or the amount of R&D employees) is hardly available. Secondly, patent databases cover patent data on small and medium enterprises, as well as on large corporations, while the alternative measures can most often be obtained only for large companies. Therefore, there is no bias towards large innovators in the patent count data. Thirdly, whereas patenting activity differs significantly across sectors, focus on one technological field is believed to provide a more meaningful comparison (Haščič & Johnstone, 2011). In fact, for the automobile sector patents are common means of protecting intellectual property and, therefore, are widely used to measure innovations (Haščič et al., 2009; Crabb & Johnson, 2010; Aghion et al., 2014).

As regards the value of patents, this issue can be solved by focusing on the triadic patents. According to OECD Patent Statistic Manual (OECD, 2009: 60), measures based on patent filings from a single patent office are subject to so-called 'home advantage', which implies that applications to the patent office are more likely to be filed by residents of the country where the office is located as compared to non-residents. For instance, as for 2005 more than 50% of the applications to the USPTO (United States Patent and Trademark Office) were applied by residents of the U.S. Consequently, filings to the single patent office are more appropriate for studies where one country is considered. The indicators that reduce this drawback are patent families (such as triadic family) and PCT applications. Patent families refer to the set of patent applications filed (and later granted) in several countries in order to protect a single invention. Triadic family is one of the most commonly used patent families due to the traditionally high technological value of the patents belonging to the family (Aghion et al., 2014). PCT applications are all the patent applications filed through the Patent Cooperation Treaty (PCT). PCT application procedure allows applicants to choose countries where their patents have force (OECD, 2009: 67), thus making PCT counts much less subject to the 'home advantage' than the patents counts based on applications to national offices. At the same time, PCT-based indicators suffer from the overall lower value of applications, as compared to the triadic family, on the grounds that the initial procedure of evaluating applications 'is not very selective' (OECD, 2009: 66). However, Haščič and Johnstone (2011) argue that when one technological field is considered, focus on only the triadic family is excessively restrictive, as it significantly reduces the amount of applications under review. At the same time, while suffering from relatively lower value, patent applications designated for several countries (such as PCT) are already thought of as having at least some technological importance, as the applicants seeks for protection in more than one country (Haščič & Johnstone, 2011). Based on these considerations, current study uses the triadic patents to measure innovating activity and implements the data on PCT applications for robustness check.

Alternatively, measures based on patent citations could be used to ensure the quality of patents. The patent citation approach requires usage of several additional databases, and therefore, is considered as a potential extension to the future research on the topic.

All in all, data on patent applications were obtained from the OECD Patent Database. The database is based on the patent data collected from the World Patent Statistical Database (or PATSTAT), maintained by the European Patent Office. The primary source has extensive records of patents filed in more than 100 patent offices around the world. PATSTAT database contains data from major patent offices, excluding only those countries where intellectual protection is weak and patenting is limited. Thus, covering almost all the patents filed in the world, the database decreases risk of sampling bias (Dechezleprêtre et al., 2015). Data in PATSTAT is presented at the level of a patent application. That is one unit of the database is a patent with all the records (date of application, name of inventor, technological field, etc.). OECD Patent Database aggregates data from PATSTAT, making it possible to conduct cross-country comparisons and to analyze patenting trend across technological fields.

Technological fields in OECD Patent Database are defined in accordance with the International Patent Classification (IPC) developed by WIPO. The classification categorizes all the patents into technologically close groups based on their content. When filed each patent is assigned at least one IPC code. For instance, patent application *EP-2080682-A3 'Control of hybrid electric vehicle during the speed control operation'* filed in the European Patent Office by *Ford Global Technologies*[4] has IPC codes *B60W20* and *B60K6*, which specify technological fields this application is related to.

All in all, the advantage of using OECD Patent Database is that the database makes it possible to extract patent data on the environment-related technologies defined by EPTI. The database aggregates the environment-friendly patents into technologically homogeneous groups based on their IPC codes. Each group is viewed as reducing environmental impacts in a specific sector[5].

This study considers several groups of environment-friendly technologies in the auto sector. These groups are defined in the following way: technologies devoted to *alternative propulsion*

[4] http://www.google.com/patents/EP2080682A3?cl=en

[5] The groups of environment-related technologies were defined by patent examiners at the EPO to distinguish technologies able to mitigate climate change: http://www.oecd.org/env/consumption-innovation/indicator.htm

(*electric or hybrid)*, technologies in emissions abatement in *internal combustion engine* and technologies directed to the improved *fuel-efficiency*. Emissions abatement technologies in ICE comprise of two sub-groups: *integrated emissions control* and *post-combustion emissions control*. As an example, the above mentioned IPC codes *B60K6* and *B60W20* refer to the group of *hybrid propulsion* technologies.

Table 1 schematically presents the groups under consideration.

Table 1. Technological fields under consideration

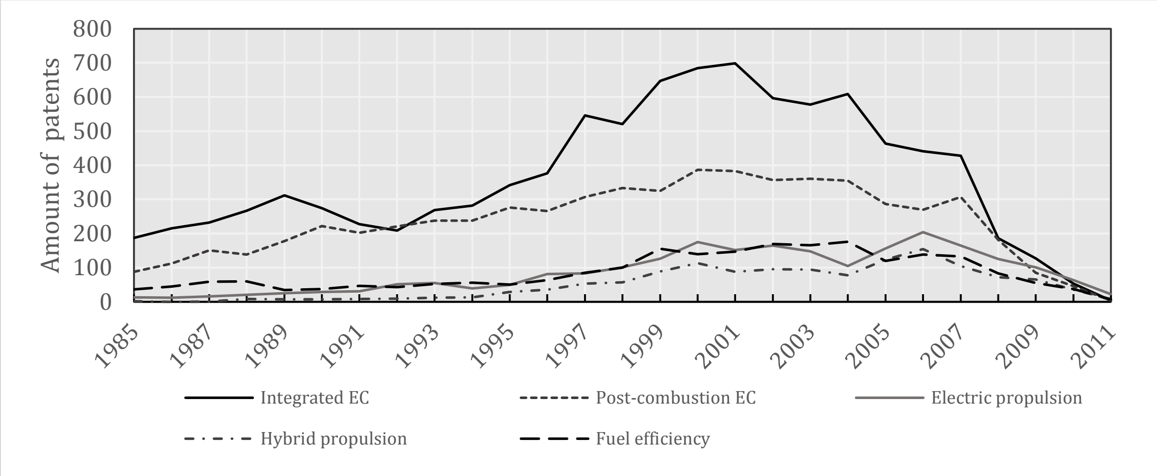
Technologies directed to alternative propulsion vehicles		Technologies directed to internal combustion engine		Technologies directed to improved fuel-efficiency
Electric propulsion	Hybrid propulsion	Integrated emissions control	Post-combustion emissions control	

In brief, technologies specific to *electric propulsion* cover developments that ensure functioning of electric motor. The group of *hybrid propulsion* includes developments directed at the performance of hybrid vehicle. Technologies in *integrated emissions control* refer to the modifications of engine design aiming at reduction of the emissions produced during combustion of fuel (Haščič et al., 2009). For example, these include fuel-infection devices, methods of controlling supply of combustible blend and monitoring exhaust gas treatment. Technologies in *post-combustion emissions control* aim at preventing evaporation of the remaining emissions (Haščič et al., 2009). An example of application falling into this category is a filter for gases and vapors. Finally, technologies in the *improved fuel efficiency* group are directed to a decreased use of fuel by engine and other non-engine parts of vehicles. Some examples are arrangements mitigating air resistance and devices for measuring air pressure.

The data on patents are available from 1985. Due to the administrative delay arising between filing the application for a patent, receiving a decision on granting the patent and actually publishing it, the data for the last couple of years is incomplete. Therefore, 2011 was chosen as the final year in the sample.

The dynamics of patenting in the above-mentioned groups is depicted in Figure 2 (triadic patents are shown). The figure reveals that innovations specific to ICE prevail over the alternative propulsion and fuel efficiency. Overall, patenting activity in all the categories has declined after 2008, quite likely due to the economic recession. However, it is evident that the amount of patents in integrated technologies started to fall earlier, approximately six years before the crisis. Post-combustion technologies demonstrated the gradual increasing trend up to 2005. Even though the alternative propulsion patents have lower share in the amount of environment-friendly patents, they have been reveling the steady growth till the recession. Similar trend has been experienced by fuel-efficiency technologies.

Figure 2. Patents in environment-friendly technologies in the auto sector, OECD, 1985-2011



Source: data obtained from OECD Patent Database

Both counts of the triadic patents and the PCT applications were collected. The recommendations provided by OECD (2009) were implemented. In particular, the patents were dated in accordance with the priority date (as opposed to the application date) [6]. The patents are assigned to countries based on the inventor's country of origin (as opposed to the applicant's origin)[7]. The largest share of patents in all the technologies under consideration is filed by Japan, the U.S., and Germany. The distribution of patents by country of inventor can be found in the Appendix (Figure A 1).

4.3.2. Prices

Major problem with collecting data on fuel prices across countries is that national statistics sources publish prices for different types of fuel and for the fuel products of different quality. The data on fuel prices appropriate for an international comparison is provided by OECD Statistics. However, the price data is available only from 1994. For this study the index for real household petrol price was used (2005 is used as a base year for the index). The data were collected for the OECD countries from 1994 to 2011. An alternative measure of fuel price could be diesel price. However, as argued by Haščič et al. (2009) and Vollebergh (2010), petrol and diesel prices are highly correlated within countries; therefore, it is enough to analyze at least one of them.

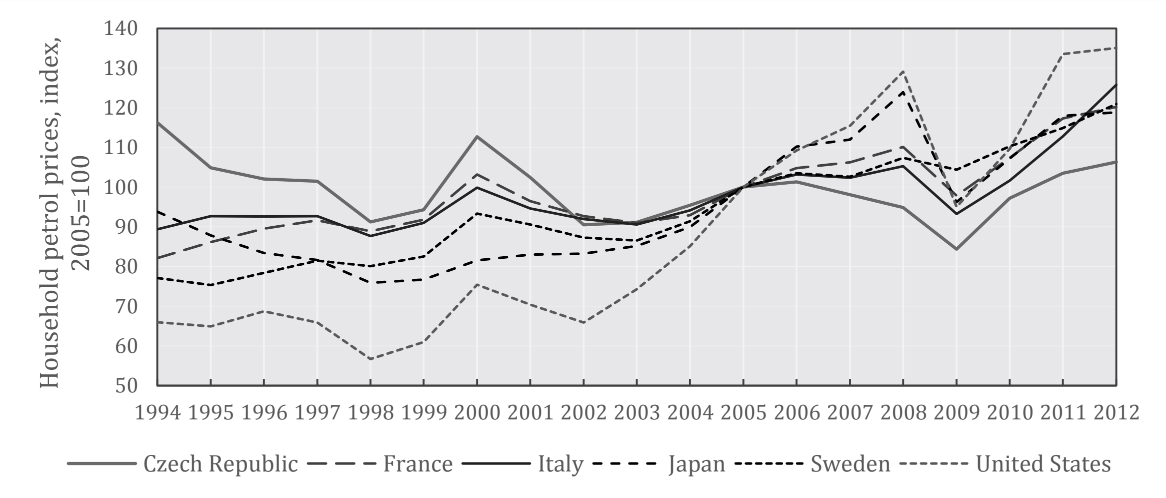
It is evident from Figure 3 that petrol prices experienced somewhat dissimilar trends. The difference in price developments arises from the discrepancy in the taxation across countries.

[6] Priority date is a date when the application was first filed to any patent office across the world. This date is thought of as the closest to the time of invention. Application date is the date when the patent application was filed at one particular office. Typically the patent is first applied for at home country and later abroad. Therefore, for one particular office the applications filed soon after the invention by residents and the ones filed with some time lag by non-residents will be considered together, which hampers the comparability (OECD, 2009).

[7] The applicant's country of origin reflects ownership of the invention, presumably capturing wealth and economic conditions, while the inventor's country of origin captures inventive activity in the country (OECD, 2009).

This discrepancy in tax-inclusive price reflects the effects of different excise taxes, value-added tax and other price regulations adopted across the OECD members.

Figure 3. Household petrol prices, index, selected countries 1994 - 2012



In fact, excise taxes on motor fuel used to vary substantially across the OECD countries, with slightly less sharp discrepancy from late 1990s, when minimum excise rates were introduced across the EU (Vollebergh, 2010). However, the difference in the tax rates across countries remains (Haščič et al., 2009).

4.3.3. Policy measures

The data on public R&D in transport sector were obtained from *IEA Energy Technology RD&D Statistics*. In addition, dummy variables were constructed for environmental standards introduced in the U.S., EU and Japan. These variables take value 1 starting from the year when the standards were introduced and equals zero otherwise. Following Haščič et al. (2009) the variables were constructed in accordance with years when most radical changes in policy stringency were introduced. In particular, variable *Tier1* takes value of 1 starting in 1994 to capture the effect of Tier1 standards in the U.S. *Tier2* equals 1 for starting from 2003. Similarly, for the EU standards variables *Euro2* takes value 1 from 1996, *Euro3* from 2000, *Euro4* from 2005 and *Euro5* from 2009. Finally, variable *JPreg* takes value 1 from 2000 to capture an increase in the stringency of policies in Japan. It should be noted that due to high correlation some of the dummy variables were dropped during the estimation.

The limitation of using these dummy variables is twofold. First, country-specific regulations are not accounted for. However, as it was mentioned before, countries differ considerably in the set of measures they implement, as well as in the practices of reporting the policy incentives, therefore, the direct comparison of policy measures for a cross-country study is problematic. Secondly, dummy variables do not reflect the degree to which the policy stringency changes. The variables are used acknowledging these limitations.

4.3.4. Sample

The resulting sample includes observations for 22 OECD countries for the period from 1994 to 2011. Unit of observation is country. Descriptive statistics are presented in Table 2.

Table 2. Summary Statistics[8]

		Observations	*Mean*	*Stand. Dev.*	*Min*	*Max*
Patents	Alternative	350	4.00	21.62	0	282
	Electric	211	2.52	13.05	0	166
	Hybrid	149	1.48	8.66	0	116
	Conventional	755	15.32	51.95	0	463
	Integrated	382	10.65	39.02	0	366
	Post-combustion	373	6.88	22.96	0	210
	Fuel efficiency	245	2.50	8.98	0	89
Determinants of patenting activity	Fuel price in *t-2*	534	4.52	0.15	3.944	5
	Knowledge stock	783	142.66	480.07	0	4084
	Spillover	783	3559.41	2533.74	0	7997
	Tier2	971	0.36	0.48	0	1
	JPreg	971	0.47	0.50	0	1
	Public R&D	574	26.32	81.41	0	912.209

[8] To make the interpretation easier, all the variables in the table are presented before the log transformation, however, observations count is presented for variables already in logarithms

5. Estimation results

This section outlines the results of econometric estimation. At the first stage, models estimating patenting activity in three groups of environment-friendly technologies are considered. Firstly, the models for *alternative propulsion* are discussed. Secondly, patenting in technologies directed at improved *fuel-efficiency* is examined. Thirdly, *ICE specific emissions control* patents are assessed. At the second stage, the estimation results for a more detailed classification of technological groups are presented. This section is devoted primarily to the estimation results; their interpretation is presented in the following section.

5.1. Stage 1: Alternative and conventional technologies

Before estimating the models a set of diagnostic tests were executed. Test results for the models estimating patenting activity in all the groups are reported jointly. Modified Wald test for the group-wise heteroskedasticity rejected the hypothesis of homoscedasticity (or constant variance), implying that the robust estimation should be performed. Results of Wooldridge test for autocorrelation allowed rejecting the hypothesis about the presence of serial correlation at 5% significance level.

Next, tests for the model choice were conducted. F-test supported the preference of fixed-effects model over the pooled OLS. Execution of Breusch-Pagan Lagrange multiplier test allowed rejecting the hypothesis about the absence of variance across countries (i.e. no panel effect), which means that random-effects model is preferred over the OLS estimation. As it is common in the empirical literature, the results are presented both types of models (fixed-effects models are indicated as FE in the heading and random-effects model as RE).

The estimation results for the group of alternative technologies are reported in Table 3. Columns (1) and (2) of Table 3 present the estimation results for the straightforward models with only the share of patents in alternative propulsion as a predictor variable (no control variables). The rest of the table contains the specifications that include additional variables. Specifications of random-effects models (2), (4), (6) and (8) incorporate dummy variables accounting for country effects (coefficients of these dummy variables are not shown in the table so as not to overload the results, the majority of them are highly significant).

Overall, the estimation results for the patents in alternative propulsion provide evidence in support of the induced innovation hypothesis, indicating that fuel prices have a positive impact on the patenting activity in the alternative technologies. It should be mentioned that both lag *t-1* and lag *t-2* were considered, as it is done by Popp (2002). Both measures give significant results. However, since relatively better fit is found for lag of two years (*t-2*), the results are reported for

lnP_{it-2}. It is evident from Table 3 that the positive effect of fuel prices is significant and stable across all the specifications. For instance, model (8)[9] shows that with 1% increase in fuel prices the patenting activity in alternative propulsion increases by approximately 0.9%[10] in future period (in two years).

Knowledge stock is significant only in two specifications and demonstrates a positive impact on patenting. A positive impact indicates that the patenting activity in alternative propulsion intensifies, when the existing base of relevant scientific knowledge expands. However, the effect is not stable for all the specifications. The coefficient of public R&D is significant and displays a positive effect. A positive effect is consistent with the assumption that governmental support for innovation fosters the research efforts in alternative propulsion. Spillover effect is insignificant.

Table 3. Estimation results. Alternative technologies

VARIABLES	(1) FE	(2) RE	(3) FE	(4) RE	(5) FE	(6) RE	(7) FE	(8) RE
Fuel price in *t-2*	2.001***	2.001***	1.648***	1.648***	1.248***	1.248***	0.899***	0.899***
	(0.454)	(0.488)	(0.456)	(0.491)	(0.271)	(0.292)	(0.282)	(0.305)
Knowledge stock			0.477	0.477	0.594*	0.594*	0.376	0.376
			(0.294)	(0.316)	(0.304)	(0.328)	(0.280)	(0.302)
Public R&D					0.002*	0.002*	0.002*	0.002*
					(0.001)	(0.001)	(0.001)	(0.001)
Spillovers							0.365	0.365
							(0.359)	(0.388)
Constant	-14.45***	-14.53***	-15.2***	-14.74***	-14.17***	-13.04***	-14.66***	-13.88***
	(2.039)	(2.159)	(2.542)	(2.502)	(1.770)	(1.555)	(2.188)	(2.325)
Observations	156	156	156	156	139	139	139	139
Number of countries	22	22	22	22	20	20	20	20
Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of alternative propulsion patents in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

[9] Hausman test shows that random-effects model should be preferred over the fixed-effects, therefore, interpretations of the coefficients are based on the random-effects specifications. Column (8) displays the random-effects model with the full set of the variables, therefore, it is the one used for the interpretation.

[10] Patenting activity is understood as the share of patents related to certain technology in the total amount of patents in the corresponding country. Since both the dependent and independent variables are presented in logarithms, the coefficients are interpreted as elasticity.

Table 4 reports the estimation results for the group of technologies directed to the improved fuel efficiency. The baseline models with no control variables are presented in columns (9) and (10). The rest of the table contains the specifications with additional variables. All the random-effects specifications include dummy variables for country effects (coefficients of these dummy variables are not presented so as not to overload the results, however, the majority of the country dummies are strongly significant).

The empirical support for the induced innovation hypothesis is found in four specifications out of eight. In particular, specifications (9), (10), (13) and (14) indicate that increase in fuel price leads to an increase in the patenting activity in fuel-efficient technologies. Specification (14) demonstrates that when fuel prices rise by 1%, patenting in fuel-efficient technologies intensifies by approximately 1.4% in two years. Knowledge stock is strongly significant for all the specifications and exhibits the positive impact on patenting. Thus, patenting in fuel efficiency increases, when volume of the available knowledge grows. Neither public R&D, nor spillover effect is significant.

Table 4. Estimation results. Fuel efficiency

VARIABLES	(9) FE	(10) RE	(11) FE	(12) RE	(13) FE	(14) RE	(15) FE	(16) RE
Fuel price in *t-2*	1.474**	1.474**	0.877	0.877	1.430*	1.430*	1.276	1.276
	(0.605)	(0.647)	(0.575)	(0.615)	(0.742)	(0.795)	(0.859)	(0.921)
Knowledge stock			0.714**	0.714**	0.749***	0.749***	0.612*	0.612*
			(0.280)	(0.299)	(0.238)	(0.256)	(0.314)	(0.337)
Public R&D					-0.001	-0.001	-0.001	-0.001
					(0.001)	(0.001)	(0.001)	(0.001)
Spillover							0.409	0.409
							(0.868)	(0.931)
Constant	-12.26***	-12.54***	-13.08***	-12.58***	-15.98***	-15.56***	-19.71**	-19.49**
	(2.714)	(2.855)	(2.459)	(2.547)	(2.660)	(2.983)	(7.881)	(8.707)
Observations	161	161	161	161	143	143	143	143
Number of countries	21	21	21	21	19	19	19	19
Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of patents directed to improved fuel efficiency in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

All in all, the models estimated for the alternative propulsion technologies and for the technologies aimed at improving fuel efficiency offer the empirical support for the induced innovation hypothesis. An additional robustness check was conducted for the alternative and fuel-efficient technologies. In particular, three major inventors in alternative technologies (the U.S., Japan and Germany) were excluded from the sample. Coefficient for price remained strongly significant and positive, signifying that the above described results are robust. Estimation results can be found in the Appendix Table A1.

The estimation results for the group of technologies specific to ICE (conventional) are displayed in Table 5. In a similar way to the previous models, the baseline models with no control variables are presented in columns (17) and (18). The rest of the table contains the specifications that contain additional variables. Specifications of random-effects models (20), (22) and (24) also include dummy variables for country effects (coefficients of these dummy variables are not presented so as not to overload the results, coefficients are highly significant).

The support for the sign predicted by Aghion et al. (2014) is found only in specifications (19) and (20) revealing that with 1% increase in fuel prices, patenting activity in ICE decreases by about 0.7% in two years. At the same time, the result is not stable over the different specifications. Control variables are not significant. Presumably, these results point to the heterogeneity of the technologies this group comprises. In other words, the estimation results motivate to conduct the analysis for a more disaggregated group of technologies.

Table 5. Estimation results. Conventional technologies

VARIABLES	(17) FE	(18) RE	(19) FE	(20) RE	(21) FE	(22) RE	(23) FE	(24) RE
Fuel price in *t-2*	-0.459	-0.459	-0.710***	-0.710***	-0.601	-0.601	-0.709	-0.709
	(0.307)	(0.324)	(0.239)	(0.252)	(0.436)	(0.461)	(0.625)	(0.660)
Knowledge stock			0.244	0.244	0.013	0.013	-0.032	-0.032
			(0.207)	(0.219)	(0.225)	(0.238)	(0.351)	(0.371)
Public R&D					0.000	0.000	0.000	0.000
					(0.001)	(0.001)	(0.001)	(0.001)
Spillover							0.097	0.097
							(0.397)	(0.419)
Constant	-2.345	-2.716*	-2.207*	-2.509**	-1.734	-2.292	-1.891	-2.484
	(1.380)	(1.439)	(1.221)	(1.242)	(2.112)	(2.172)	(2.090)	(2.195)
Observations	266	266	266	266	228	228	228	228
Number of countries	28	28	28	28	24	24	24	24
Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of conventional (ICE specific) patents in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

The models with policy dummies are reported in Table 6. The dependent variable is indicated in the heading (*Alt* stands for alternative technologies, *Fueleff* – fuel-efficient and *Conv* – specific to ICE). Significance of coefficients found in models without policy dummies holds for the specifications with alternative technologies. Specification for fuel-efficient innovation reveal no significant coefficients among the controls, the same hold for ICE patents. As for policy dummies, in specifications (25), (27) and (28) variable *Tier2* approximating an increase in stringency of standards in the U.S. in 2003 reveals a positive significant impact on the patenting activity. This result means that increase in stringency of policies in the U.S. in 2003 provoked patenting activity in the technologies directed to lower use of fossil fuel – technologies in alternative propulsion and in fuel efficiency. Whereas according to the estimation results, technologies in ICE were unaffected by the policy shock. Intuitively this means that high standards on the emission output stipulated by Tier 2 raised incentives of auto makers to invest in technologies which avoid usage of fossil fuel, rather than to develop technologies in ICE that incrementally decrease emission output.

Table 6. Estimation results of models with policy dummies.

	(25)	(26)	(27)	(28)	(29)	(30)
	FE	RE	FE	RE	FE	RE
VARIABLES	*Alt*	*Alt*	*Fueleff*	*Fueleff*	*Conv*	*Conv*
Fuel price in *t-2*	0.758*	0.758*	0.850	0.850	-0.669	-0.669
	(0.367)	(0.396)	(0.726)	(0.779)	(0.574)	(0.607)
Knowledge stock	0.540**	0.540**	0.395	0.395	-0.001	-0.001
	(0.232)	(0.250)	(0.346)	(0.372)	(0.346)	(0.366)
Public R&D	0.002*	0.002	-0.001	-0.001	0.000	0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Spillover	-2.260	-2.260	-0.376	-0.376	-0.806	-0.806
	(1.309)	(1.415)	(1.353)	(1.452)	(1.049)	(1.109)
JPreg	0.447	0.447	0.084	0.084	0.208	0.208
	(0.305)	(0.329)	(0.344)	(0.369)	(0.264)	(0.279)
Tier2	0.425*	0.425	0.396*	0.396*	0.095	0.095
	(0.243)	(0.263)	(0.198)	(0.213)	(0.172)	(0.181)
Constant	16.069	16.902	-7.113	-7.330	8.505	7.888
	(16.765)	(17.919)	(15.080)	(16.018)	(11.818)	(12.493)
Observations	139	139	143	143	228	228
Number of countries	20	20	19	19	24	24
Country FE	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is indicated in headings. *Alt* stands for alternative technologies, *Fueleff* – fuel-efficient and *Conv* – specific to ICE.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

5.2. Stage 2: More detailed view

Similar to the first stage, the diagnostic tests for more disaggregated groups of technologies pointed to the need for robust estimation. The hypothesis about the presence of serial correlation was rejected at 5% significance level. F-test supported the preference of fixed-effects model over the pooled OLS. Execution of Breusch-Pagan Lagrange multiplier test revealed that random-effects model is preferred over the OLS estimation.

The results of econometric analysis for the share of patents in the electric propulsion are shown in Table 7. The results are consistent with the induced innovation hypothesis. It is evident from Table 7 that the positive effect of fuel prices on patenting in electric propulsion technologies is significant and stable across all six specifications. On the example of specification (34) it can be concluded that when fuel prices rise by 1%, the patenting activity in electric propulsion increases by approximately 1% in two years. Neither knowledge stock, nor spillover effect are significant. The coefficient of public R&D is significant and displays a positive effect. Specifications (35) and (36) already include policy dummies and reveal a positive significant impact of rise in policy stringency in Japan on the patenting activity in electric propulsion. This effect is partly driven by the fact, that Japan has a great share of patents in this type of technology.

Table 7. Estimation results. Electric propulsion

VARIABLES	(31) FE	(32) RE	(33) FE	(34) RE	(35) FE	(36) RE
Fuel price in *t-2*	1.072**	1.072**	1.040**	1.040**	1.315**	1.315**
	(0.438)	(0.473)	(0.374)	(0.404)	(0.526)	(0.569)
Knowledge stock	0.392	0.392	0.370	0.370	0.395	0.395
	(0.381)	(0.411)	(0.449)	(0.485)	(0.445)	(0.481)
Public R&D	0.002**	0.002**	0.002**	0.002**	0.002*	0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Spillover			0.037	0.037	-1.193	-1.193
			(0.368)	(0.398)	(0.896)	(0.968)
JPreg					0.586*	0.586*
					(0.303)	(0.327)
Tier2					0.181	0.181
					(0.317)	(0.342)
Constant	-12.889***	-12.675***	-12.941***	-12.766***	-4.149	-4.025
	(2.680)	(2.457)	(2.943)	(3.059)	(7.131)	(7.656)
Observations	125	125	125	125	125	125
Number of countries	18	18	18	18	18	18
Country FE	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of electric propulsion patents in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

However, as it is argued above, stringency of policies in one country matters for foreign countries. Perkins and Neumayer (2012) point out that in the auto sector competition, as well as willingness to receive FDI and to comply with the import standards force manufacturers to adjust product standards up to the level of countries with more stringent regulations. Thus, the significance of Japanese regulations of 2000 is believed to also capture this effect. It is worth mentioning, that rises in policy stringency reveal much stronger impact than public R&D expenditure.

The estimation results for the share of patents in the hybrid propulsion presented in Table 8 reveal a similar picture. The results are also consistent with the induced innovation hypothesis, indicating that increase in fuel prices spurs patenting in hybrid technologies. Table 8 reports significant and quite stable effect of fuel prices on patenting activity. Thus, for specification (40) a 1% increase in fuel prices leads to an increase in the patenting activity in hybrid propulsion of around 1.1% with a two-year lag. Knowledge stock is highly significant for two specifications, but addition of a spillover variable mitigates the effect. For hybrid specifications public R&D is not significant. At the same time both policy dummies reveal positive significant impact on patenting activity in hybrid propulsion. Toughening of stringency in Japan in 2000, as well as in the U.S. in 2003 reveal stimulating effect on patenting activity in hybrid propulsion.

Table 8 Estimation results. Hybrid propulsion

	(37)	(38)	(39)	(40)	(41)	(42)
VARIABLES	FE	RE	FE	RE	FE	RE
Fuel price in *t-2*	1.386**	1.386*	1.126*	1.126*	0.302	0.302
	(0.656)	(0.718)	(0.569)	(0.622)	(0.525)	(0.575)
Knowledge stock	0.836***	0.836***	0.575	0.575	0.232	0.232
	(0.279)	(0.305)	(0.354)	(0.387)	(0.405)	(0.444)
Public R&D	0.001	0.001	0.001	0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Spillover			0.843	0.843	-2.610	-2.610
			(1.121)	(1.227)	(2.252)	(2.469)
JPreg					0.775*	0.775*
					(0.376)	(0.412)
Tier2					0.717*	0.717*
					(0.349)	(0.382)
Constant	-17.085***	-14.462***	-25.065*	-22.917	22.913	23.910
	(2.742)	(2.995)	(12.408)	(14.104)	(28.545)	(31.239)
Observations	108	108	108	108	108	108
Number of countries	18	18	18	18	18	18
Country FE	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of hybrid propulsion patents in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table 9 displays the specifications where dependent variable is the share of patents in integrated emissions control technologies. Integrated emissions control technologies constitute the part of environment-friendly technologies specific to ICE. It can be seen from Table 9 that price coefficient is negative and significant. This result is consistent with findings reported in the model estimated for the group of ICE patents (Table 5, columns 19 and 20). However, the overall results reported for ICE were weak (fuel price coefficient was not stable across several specifications) and control variables were not significant. Whereas, for this sub-group, more significant results are found. The significance of price holds for three specifications out of six. Interpretation of the fuel price coefficient for specification (45) is that with 1% increase in price, patenting activity in integrated emissions control declines by 1.3%. In general, the negative sign is in line with the finding by Vollebergh (2010) for emission abatement technologies and with theoretical prediction of the model in Aghion et al. (2014).

Apart from fuel price, knowledge stock coefficient gains significance. The coefficient is negative, indicating that greater knowledge stock discourages innovation in this type of technologies. This finding is consistent with the finding reported by Popp (2002) that some technological fields experience the diminishing returns from the research output. Diminishing returns signify that it becomes more difficult to make new discoveries; more efforts are needed to generate innovations. Diminishing returns can arise, when knowledge in the field is already extensive, approaching to the technological frontier.

Table 9. Estimation results. Integrated emissions control

	(43)	(44)	(45)	(46)	(47)	(48)
VARIABLES	FE	RE	FE	RE	FE	RE
Fuel price in *t-2*	-0.401	-0.401	-1.316*	-1.316	-1.575**	-1.575**
	(0.858)	(0.911)	(0.762)	(0.809)	(0.736)	(0.783)
Knowledge stock	-0.015	-0.015	-1.658	-1.658	-1.991**	-1.991**
	(0.534)	(0.566)	(1.061)	(1.127)	(0.909)	(0.967)
Public R&D	-0.000	-0.000	-0.000	-0.000	0.000	0.000
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Spillover			1.295**	1.295**	1.233*	1.233*
			(0.587)	(0.623)	(0.696)	(0.740)
JPreg					-0.061	-0.061
					(0.251)	(0.267)
Tier2					-0.338*	-0.338*
					(0.177)	(0.188)
Constant	-2.728	-3.020	4.462	2.343	-31.458*	-33.976*
	(4.253)	(4.145)	(5.326)	(4.728)	(17.080)	(18.182)
Observations	200	200	200	200	200	200
Number of countries	23	23	23	23	23	23
Country FE	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of integration technologies patents in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Moreover, spillover effect becomes significant, indicating that the innovative activity in integrated emissions control benefits from the knowledge obtained from abroad. Combined with the diminishing returns of country's own knowledge stock, this favorable effect of spillovers may signify that external knowledge revives the existing scientific base.

Public R&D is not significant. As for the policy dummies, the variable denoting increase of policy stringency in the U.S. (*Tier2*) reveals a negative significant impact on patenting. This result may be associated with the fact that Tier 2 introduced quite dramatic reduction in the emission output constituting about 81% decrease in NOx emissions for cars and 93% for trucks as compared to Tier 1 (OECD, 2004: 102). It is argued that such a drastic change in requirements put much pressure on automakers, what could have had discouraging effect on incentives to search for technological solutions compliant with new requirements (Vollebergh, 2010).

The estimation results for the patents in post-combustion emissions control are reported in Table 10. Price coefficients are insignificant for all the specifications, revealing no effect of price on patenting in post-combustion technologies. This finding is consistent with conclusion made for a more narrow set of post-combustion technologies by Haščič et al. (2009).

Table 10. Estimation results. Post-combustion emissions control

VARIABLES	(49) FE	(50) RE	(51) FE	(52) RE	(53) FE	(54) RE
Fuel price in *t-2*	0.695	0.695	0.777	0.777	0.826	0.826
	(0.696)	(0.737)	(0.751)	(0.796)	(0.707)	(0.750)
Knowledge stock	-0.140	-0.140	-0.039	-0.039	-0.166	-0.166
	(0.405)	(0.429)	(0.709)	(0.752)	(0.652)	(0.693)
Public R&D	-0.001	-0.001	-0.001	-0.001	-0.001	-0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Spillover			-0.088	-0.088	-1.620*	-1.620*
			(0.467)	(0.495)	(0.835)	(0.887)
JPreg					0.557**	0.557**
					(0.250)	(0.266)
Tier2					0.092	0.092
					(0.164)	(0.174)
Constant	-6.909**	-7.452***	-7.412**	-7.822***	-22.656	-23.079
	(2.475)	(2.379)	(3.520)	(2.995)	(14.224)	(15.329)
Observations	195	195	195	195	195	195
Number of countries	22	22	22	22	22	22
Country FE	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO

Notes: The dependent variable is logarithm of the share of post-combustion technologies patents in total amount of patents in the country under consideration.
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Neither knowledge stock, nor public R&D are significant. Spillover effect has a negative significant coefficient, indicating that the volume of knowledge obtained from overseas hinders patenting activity in this type of technology. On the one hand, this result may point to even stronger level of diminishing returns in this technological field (even external knowledge flows hardly add anything to the already existing ideas). On the other hand, the existence of spillovers may incur unwanted leakage of knowledge, which decreases returns to scientific efforts of the inventor (Kaiser, 2002). Thus, the negative influence of knowledge spillover may be associated with harmful effects of knowledge accessibility.

Finally, it is evident from Table 10 that rises in policy stringency in Japan in 2000 had stimulating effect on patenting activity in post-combustion emissions control. This result is consistent with findings presented in Haščič et al. (2009), who show that policy shocks are key determinants in post-combustion innovations.

Estimation was also conducted for PCT applications. In general, for the majority of the specifications the coefficients are consistent with the above described models. Whereas for some models devoted to ICE patents fit of the models is much weaker. This result may arise from recognized lower value of applications filed through PCT (OECD, 2009: 66). Estimation results can be found in the Appendix (Table A2).

6. Discussion

This section discusses the above described results. All in all, the econometric analysis provides the empirical support for the induced innovation hypothesis. The results are consistent with the theoretical considerations discussed by Popp (2002) and Aghion et al. (2014). More specifically, the estimation results of the models for alternative propulsion and for the technologies aimed at improving fuel efficiency are consistent with the prediction that increase in fuel price spur innovation directed at lower use of the fuel. The inducing effect of fuel price on fuel-efficient innovation in the auto sector is in line with the empirical findings by Crabb and Johnson (2010), Haščič and Johnstone (2011), and Aghion et al. (2014). Moreover, it was shown that innovations in technologies directed at lower use of petrol-based fuel, are fostered by the existing knowledge base. Thus, according to the analysis, when the existing base of relevant scientific knowledge expands, patenting activity in alternative propulsion and fuel efficiency intensifies. It was also found that toughening of policy stringency in large auto markets promotes patenting in these types of technologies.

A comparison between the results obtained for patenting in electric and in hybrid technologies reveals some dissimilarities. First, the magnitude of the price effect seems to be slightly higher for hybrid patents. In other words, patenting in hybrid propulsion is to some extent more sensitive to rise in prices. This finding is consistent with Haščič and Johnstone (2011: 118), who argue that since hybrid technologies involve less radical changes, they are easier for manufacturers to develop and implement, therefore, hybrid technologies may be more attractive to develop in response to rising prices. This logic is also applicable to the finding that policy shocks have stronger effect on hybrid technologies, than on electric ones. At the same time, public R&D expenditure was found to be significant only for electric technologies, but not for hybrid. Greater importance of public support for electric technologies may arise due to the fact, that expansion of electric motor vehicles requires more extensive infrastructure, which can hardly be fully supplied by manufacturers (OCED, 2004: 12). It is noteworthy, that changes in policy stringency have much stronger impact on innovating activity than public R&D expenditure. In fact, it is argued by Fisher and Newell (2008) that in promoting green technologies emission standards are more efficient than R&D support, as they give stronger incentives to manufacturers.

As regards technologies related to ICE the analysis reveals the dissimilar nature of the technologies comprising the group of ICE. Thus, the analysis conducted separately for integrated and post-combustion emissions control demonstrates that these sub-groups of technologies are driven by different factors. In fact, price is a determinant of the former technology, while does not influence the latter. In general, the negative impact of fuel price on integrated technologies conforms to the theoretical prediction by Aghion et al. (2014) that rising fuel price discourages innovations in technologies related to ICE. In interpretation by Vollebergh (2010) inverse relationship between innovation in ICE and fuel price reflects the fact that manufacturers expect consumers to switch to vehicles, which require lower use of expensive fuel, therefore, manufacturers reduce their investment in ICE related technologies. Given that price effect on patenting in alternative propulsion and fuel efficiency has the opposite sign, Vollebergh's interpretation corresponds well with the estimation results. The difference in reaction of post-combustion and integrated technologies to price changes may arise from the different nature of the benefits these technologies engender. In particular, Haščič et al. (2009) argue that integrated technologies have both private and public benefits (as they both reduce emission output and reduce maintenance costs), whereas post-combustion technologies bring only public benefits (only reduce emissions). Existence of private benefit involves private incentives, implying that when making the decision about whether to invest in technology or not, manufacturer analyzes profitability prospects. Whereas in the absence of private incentives, there are no incentives related to the expected return on innovation. Therefore, it is policies that force implementation of such technologies (Haščič et al., 2009).

At the same time, policy shocks seem to have the diverging effect on the patenting activity in these technologies. Patents in integrated emissions control are found to be suppressed by Tier 2 standards, whereas Japanese policy shocks were found to trigger innovation in post-combustion technologies. The negative effect of regulation measures on emission abatement innovation is also documented by Vollebergh (2010), who claims that sharp tightening of environmental standards may discourage manufacturers from investing in already established technologies. The fact that the same standards were found positively significant for hybrid patents may imply that instead of trying to comply with strict regulations by incrementally improving the existing technologies, manufacturers preferred exploring alternative promising developments. The difference in reaction of post-combustion and integrated technologies to policy shocks may again arise from the different nature of the benefits these technologies generate.

As regards the overall effect of fuel prices on environment-friendly technologies, the analysis reveals that higher price stimulates innovation in alternative propulsion and in fuel-efficiency technologies, whereas it discourages the innovative activity in integrated emissions. When prices go up by 1%, patenting in alternative propulsion expands by around 1%, patenting in fuel efficiency by 1.4%, whereas patenting in integrated emissions control shrinks by approximately 1.6%. This notion implies that when policymakers develop tax design for fuel price, they have to deal with the trade-off between fuel efficiency and emission abatement.

The analysis has several policy implications. The results indicate that petrol taxes (or related means such as carbon taxes) can spur patenting activity in alternative propulsion and in fuel efficiency[11]. Thus, when oil prices plummet, policymakers willing to promote technologies directed at lower use of fuel, should reconsider approaches to tax design. Meanwhile, patenting in integrated emissions control is suppressed by increase in prices, engendering a need for a trade-off in policy objectives. Moreover, the analysis reveals that changes in policy stringency would yield much stronger impact on innovating activity than public R&D expenditure. Certainly, feasibility of policies should be taken into account when developing policy design.

The important implications for the research design can be derived from the present paper. First of all, the study reveals that the analysis conducted on a more disaggregated level yields more distinct results. When feasible, technological groups should be divided into more homogeneous sub-groups. Then it is possible to grasp the differing nature of technology diffusion. Secondly, the analysis points out that the choice of patent measure matters for the result. As it was mentioned, estimations conducted for PCT-based measure were found less significant, which is most likely caused by lower quality of patents in the PCT sample. Overall, it is recommended to use several measures when performing empirical investigation.

Several propositions for perspective research on the topic follow from this study. Firstly, it might be interesting to go beyond the induced innovation hypothesis to assess other possible determinants of innovative activity in auto industry. For instance, consumer preferences, prices of alternative fuels, prices of vehicles, or the extent of available infrastructure could be explored in relation to the patenting activity. The above mentioned theoretical considerations contributed by Acemoglu (2002) and Fouquet (2010) could also be also evaluated. Secondly, it could be interesting to find an approach for assessing policy stringency in greater detail. For instance, index approximating actual stringency in standards could be developed. Next, firm level analysis would most likely shed more light on firm-specific drivers of innovations in the sector. Finally, the role of technological progress in complementary industries would be interesting to look at.

[11] Obviously, these implications should not be understood as a call for excessively high taxes. Obviously, other economic issues (such as Laffer curve) should be taken into account when designing policy. The discussion of proper design of such policies is out of scope of this paper.

7. Conclusion

The paper has examined the effect of fuel prices on environment-related innovations in the auto industry. In particular, the induced innovation hypothesis was tested for several groups of technologies with promising environmental impact. Econometric analysis was conducted using data on the OECD countries from 1994 to 2011. Theoretical and empirical approach of the paper was based on recent developments by Popp (2002) and Aghion et al. (2014).

The analysis reveals that innovations in alternative propulsion systems are indeed induced by fuel prices. In fact, both technologies in electric and hybrid propulsion are found to be positively related to fuel price. The same effect holds for the technologies directed to improved fuel efficiency. These findings support the induced innovation hypothesis. In addition, it was mentioned that innovations in technologies directed at lower use of fossil fuel, are fostered by the existing knowledge base. Thus, when the existing base of relevant scientific knowledge increases, patenting activity in alternative propulsion and fuel efficiency goes up. It was also shown that toughening of policy stringency in large auto markets stimulates patenting in these types of technologies. The effects of policy standards were found to have stronger effect on patenting than the effects of public R&D expenditure.

The estimation results suggest that two types of environment-related innovations directed to internal combustion engine respond differently to price increases. It was shown that patents in integrated emissions control are sensitive to fuel prices and are negatively affected by their increase. Whereas there is no such effect for post-combustion technologies. At the same time, post-combustion innovations are fostered by policy shocks, while for the integrated technologies the policies reveal a suppressing effect.

Overall, the findings suggest that the decisions of policymakers about the rates of fuel and carbon taxes will influence the direction of technological change in the auto industry. In particular, an increase in tax rates is expected to redirect innovative activity towards the technologies that attempt to reduce the use of fossil fuels. In addition, policy standards can be considered as a supportive policy measure. However, it should be realized that the overall environmental impact of such redirection will still depend on the type of fuel used to generate electric power for the alternative propulsion.

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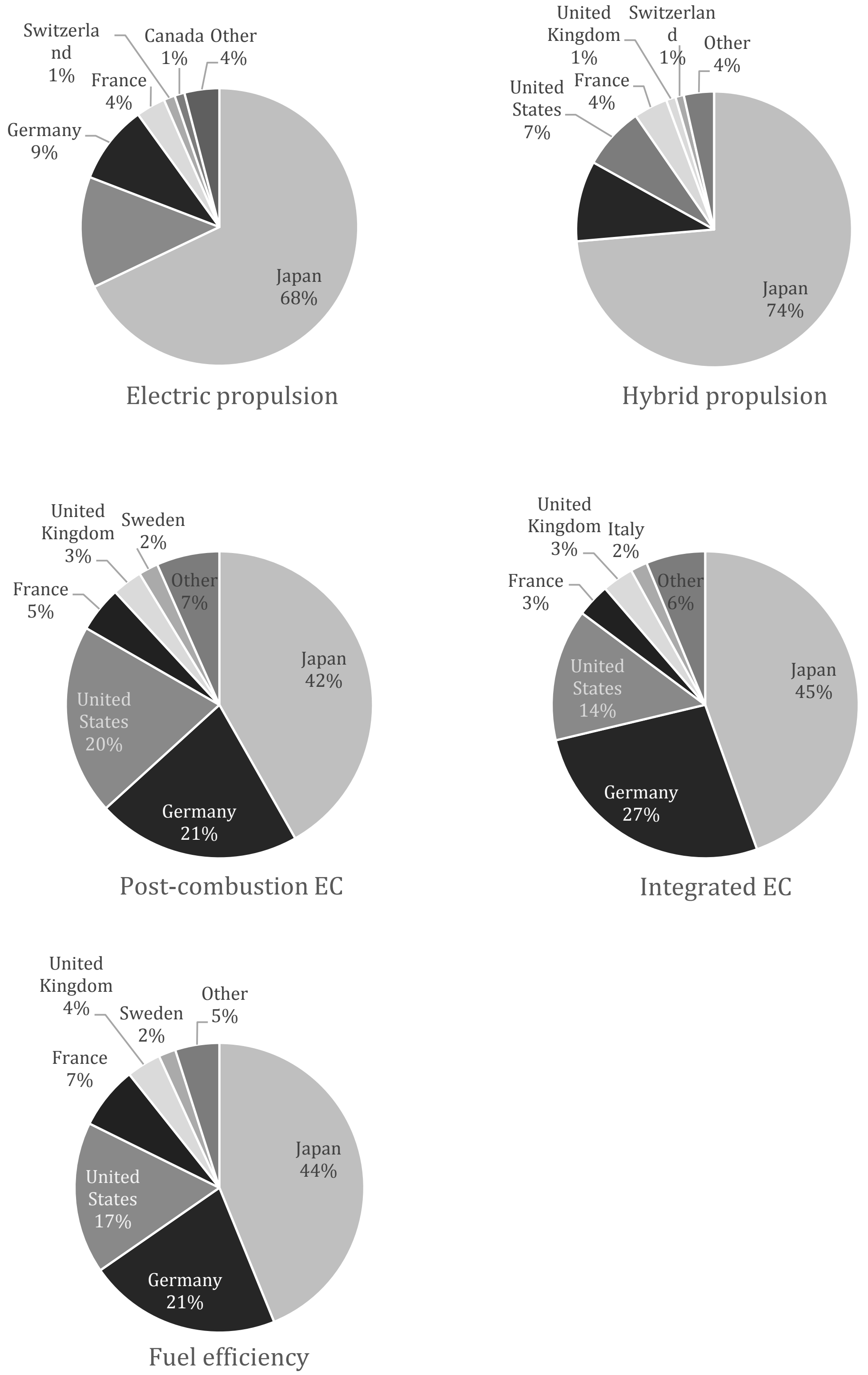
Appendix

Figure A 1 Patenting in environment-friendly technologies, by inventor country



Note 1 Jaffe's index adapted from Verdolini and Galeotti (2011)

In his paper Jaffe (1986) has developed a measure that allows comparing technological proximity of firms by comparing the portfolio of the patents these firms hold. Verdolini and Galeotti (2011) have adapted this index to a country level. The portfolio of patents constitutes of country i constitutes a vector Sh_i containg shares of patents granted in s technological fields $Sh_i = (sh_{i,1}, sh_{i,2}, \dots, sh_{i,s})$. The index is calculated as coefficient of uncentered correlation between a pair of vectors. Thus, the index $TP_{i,j}$ is calculated for each pair of countries (*i, j)* using the following formula:

$$w_{i,j} = \frac{(Sh_i' Sh_j)}{\left[\sum_s (sh_{i,s})^2 \sum_s (sh_{j,s})^2\right]^{1/2}}$$

The measure takes values from zero to one. Value of one indicates that vectors of i and j are identical.

Table A1. Estimation results. Alternative technologies. Major producers of alternative technologies excluded (The U.S., Germany and Japan).

	1	2	3	4
VARIABLES	FE	RE	FE	RE
	Alt	*Alt*	*Fueleff*	*Fueleff*
Fuel price in *t-2*	1.123*	1.123*	2.934*	2.934
	-0.545	-0.603	(1.665)	(1.820)
Knowledge stock	0.334	0.334	0.635	0.635
	-0.42	-0.465	(0.487)	(0.532)
Public R&D	0.015***	0.015***	-0.035	-0.035
	-0.002	-0.002	(1.515)	(1.656)
Spillover	0.047	0.047	-0.001	-0.001
	-0.861	-0.954	(0.003)	(0.004)
Constant	-12.723	-12.184	-21.161	-21.342
	-8.63	-9.604	(12.247)	(13.468)
Observations	92	92	97	97
Number of countries	17	17	16	16
Country FE	YES	YES	YES	YES
Year FE	NO	NO	NO	NO

Notes: *Alt* indicates the share of alternative propulsion patents in total amount of patents in the country. *Fueleff* – measure of fuel efficiency patents. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A2. Estimation results for PCT applications

VARIABLES	(1) FE *Alt*	(2) RE *Alt*	(3) FE *Alt*	(4) RE *Alt*	(5) FE *Electric*	(6) RE *Electric*	(7) FE *Hybrid*	(8) RE *Hybrid*
Fuel price in *t-2*	1.495**	1.495**	1.084*	1.084*	1.381*	1.381*	0.946*	0.946
	(0.627)	(0.665)	(0.584)	(0.620)	(0.676)	(0.716)	(0.537)	(0.577)
Knowledge stock	0.333*	0.333*	0.200	0.200	0.303*	0.303	0.544***	0.544***
	(0.172)	(0.182)	(0.269)	(0.286)	(0.175)	(0.185)	(0.116)	(0.124)
Public R&D	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Spillover			0.269	0.269				
			(0.344)	(0.364)				
Constant	-14.39***	-14.85***	-15.43***	-15.92***	-14.17***	-14.61***	-13.97***	-13.87***
	(2.328)	(2.490)	(3.021)	(3.256)	(2.461)	(2.654)	(2.379)	(2.571)
Observations	247	247	247	247	224	224	195	195
Number of countries	28	28	28	28	25	25	26	26
Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO	NO	NO

Note: Shortened name of the dependent variable is indicated in the heading
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A3. Estimation results for PCT applications, cont.

VARIABLES	(9) FE *Conv*	(10) RE *Conv*	(11) FE *Integr*	(12) RE *Integr*	(13) FE *Post*	(14) RE *Post*	(15) FE *Fuel eff*	(16) RE *Fuel eff*
Fuel price in *t-2*	-0.477	-0.477	-0.616	-0.616	-0.441	-0.441	-0.436	-0.436
	(0.769)	(0.806)	(0.504)	(0.527)	(0.393)	(0.414)	(0.536)	(0.568)
Knowledge stock	0.070	0.070	-0.378**	-0.378**	-0.442**	-0.442**	-0.656	-0.656
	(0.260)	(0.272)	(0.156)	(0.163)	(0.187)	(0.197)	(0.478)	(0.506)
Public R&D	0.000	0.000						
	(0.001)	(0.001)						
Spillover	0.107	0.107	0.369**	0.369**	0.561**	0.561**	0.710*	0.710
	(0.323)	(0.339)	(0.147)	(0.154)	(0.225)	(0.237)	(0.411)	(0.435)
Constant	-4.597*	-4.912*	-2.393	-2.462	-4.475***	-5.468***	-4.449**	-5.287**
	(2.469)	(2.591)	(1.780)	(1.834)	(1.514)	(1.583)	(2.114)	(2.153)
Observations	305	305	360	360	319	319	257	257
Number of countries	28	28	28	28	25	25	26	26
Country FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	NO	NO	NO	NO	NO	NO

Note: Shortened name of the dependent variable is indicated in the heading
Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1