Linking Induced Technological Change, Competitiveness and Environmental Regulation: Evidence from Patenting in the U.S. Auto Industry

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2007
Industry Studies Association
Working Papers

WP-2007-35
http://isapapers.pitt.edu/

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ABSTRACT

This article examines firms' innovation activities in response to U.S. technology-forcing auto emissions standards enacted between 1970 and 1998. Patent applications in automobile emission control technologies were used as a measure of firms' innovative responses to regulatory pressures. In addition, we extensively studied secondary literature and industry specific records and conducted targeted interviews with experts involved in the development. Findings of this study provide new evidence that supports the *Porter hypothesis*: the performance based technology-forcing auto emissions regulations induced technological innovation and led domestic U.S. firms to become relatively more innovative when compared to their foreign rivals. Overall, this study suggests that properly technology-forcing regulations have the potential to induce technological innovation, in particular radical innovation. Findings also imply that domestic firms may establish competitive advantage over rival firms by reacting proactively in the early phase of the regulatory era.

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* The authors of this article would like to thank Peter Thomson, Edward S. Rubin, M. Granger Morgan, David Gerard, and John Ettlie for their constructive feedbacks. We also thank seminar participants at the Carnegie Mellon University, the Academy of Management Conference, Innovation Research Network (IRN) Conference, the International Conference on Technology Policy and management, and the International Motor Vehicle Program (IMVP). Funding for this work was provided by the Department of Engineering and Public Policy (EPP) at Carnegie Mellon University, the IMVP, and the National Science Foundation (Award 522190).
Any errors remain our own.

INTRODUCTION

The idea that firms under stringent regulations may benefit from regulation-driven innovation has spurred extensive debates among academics. In a couple of influential articles, Porter and van der Linde crystallized the hypothesis that properly designed regulatory standards stimulate innovation and business opportunities that offset any costs incurred in complying with those same regulation (Porter & van der Linde, 1995a b). Supporters of what became known as the *Porter hypothesis* claim that, in the contemporary business environment of dynamic competition, firms are typically not resource-efficient. Thus, regulations could induce firms to identify efficiency gaps between the actual point of production and the production possibility frontier as to meet the new challenges set forth by the directive; regulations also provide opportunities for improved resource efficiencies to create the optimal scenario of achieving competitiveness while complying with regulatory requirements. Moreover, the greater the differences in regulatory stringencies between the US and other countries, the more likely are US firms involved in international trade to enjoy first mover advantages over firms in other countries (Porter & van der Linde 1995b), thus becoming more capable than their foreign rivals (e.g., Nert 1996). As a result, regulation driven *innovation* could *offset* any negative effect of regulation (Porter & van der Linde, 1995b; DeCANIO, 1997; Gabel & Sinclair-Desgagne, 2001). This perspective is consistent with Jaffe, Peterson, and Portney ’s (1995) well-known finding that environmental regulation does not seem to harm the competitiveness of U.S. manufacturing firms. Academics with an opposing view, however, defy the above scenario (Barbera & McConnell, 1990; Walley & Whitehead, 1994; Palmer, Oates & Portney, 1995; Greenstone, 2002). They claim that costs of environmental regulation are significantly higher than what can be compensated through innovation; and regulatory compliance costs tends to prevent firms from reaping positive financial returns from devising and operating their own environmental programs (Walley & Whitehead, 1994). Palmer et al. (1995) also discredit innovation offsets as responsible for Jaffe et al.'s (1995) findings. They argue that the cost of complying with environmental regulations is only a small portion of total costs, and that the differences in the stringency of regulatory standards between the U.S. and other major countries are not significant enough to become a source of competitive advantage (Palmer et al., 1995).

Some recent studies have begun to provide some support to the notions behind the *Porter hypothesis*. Theoretical work has explored conditions under which environmental regulation can be beneficial for industry (DeCANIO 1997; Scott 1997; Feess & Muehlheusser 2002; Mohr 2002; Greaker 2006).For example, Mohr (2002) shows that environmental policy may benefit competitiveness, provided that the level of strictness spurs the use of new abatement techniques, while Greaker (2006) suggests that competitiveness benefits can result from spillovers associated with new entry into the upstream abatement equipment sector. Similarly, some empirical analyses suggest that regulations can induce competitiveness (Jaffe & Palmer, 1997; Pickman, 1998; Boyd & McClelland, 1999; Brunnermeier & Cohen, 2003; Popp, 2003; Roediger-Schluga, 2003; Taylor, Rubin & Hounshell, 2005; Triebswetter & Hitchens, 2005). Yet, this literature is still quite underdeveloped (Jaffe, Newell & Stavins, 2002; SQW, 2006). Not only are there few studies, but they are often descriptive (Roediger-Schluga, 2003) or at an aggregate level (Pickman, 1998; Brunnermeier and Cohen, 2003; Triebswetter and Hitchens, 2005) and the findings are far from converging (Barbera & McConnell, 1990; Walley & Whitehead, 1994; Palmer et al., 1995; Greenstone, 2002).

A critical step to further our understanding on the reach of *Porter Hypothesis* is to recognize the variety of policy instruments and explore how they condition pollution abatement technological innovation. In particular, it is important to distinguish between market-based mechanisms (MBM) and command-and-control (CAC) policies. Existing perspectives suggest that MBM, which include tools such as auctioned permits and emission taxes provide greater incentives for firms to promote technological change compared to CAC type regulations, which rely on prescribing rules and standards. The latter are also seen as being inefficient because firms are regulated under a uniform standards and face similar pollution control burden, regardless of their costs to do so (Downing & White, 1986; Milliman & Prince, 1989; Jung, Krutilla & Boyd, 1996; Requate & Unold, 2003).

Despite CAC regulations' seemingly inflexible regulatory structure, recent work supports the notion that CAC type regulations can offer incentives for R&D and induce innovation. In particular, Popp (2003) and Taylor et al. (2005) provide evidence that CAC regulations on SO_2 emissions stimulated innovation that led to lowering the costs of complying with the regulation. However, CAC regulations considered by Popp (2003) and Taylor et al. (2005) represent only part of the universe of CAC regulation. These are based on the notion that firms are required to use the Best Available Control Technology (BACT), which for the SO_2 case meant scrubber technology. But CAC regulations can also be *performance –based* if firms are mandated to follow certain performance standards, with no indication of a particular technology (Leone, 1999; Jaffe et al., 2002). No previous empirical work has focused on the impact of performance-based, technology-forcing CAC regulations on innovation.

In this article, we examine the case of the automobile emission control regulations from 1970 to 1998. Automobile emission control regulation is a case of a performance-based, technology-forcing CAC regulation. In 1970, the Environmental Protection Agency (EPA) required 90% reductions in the hydrocarbons (HC) and carbon monoxide (CO) emissions from automobile tailpipes to be achieved by 1975—The Clean Air Act Amendment of 1970 (CAAA1970). Over the following years, subsequent reductions were demanded by the EPA. Using these regulatory decisions and a firm level panel data with all patents in automobile emissions control technologies,, this research aims to contribute to the literature by empirically investigating the potential linkage between technology-forcing performance-based CAC regulations and technological innovation. In particular, we aim to achieve two objectives: (1) determine whether firms' overall innovative activities are associated with the onset of technology-forcing standards; and (2) investigate whether U.S. technology-forcing regulations in automobile emissions control leads U.S. firms to become more innovative, compared to foreign firms operating in the U.S. auto industry; that is, whether the U.S. firms enjoyed the "innovation-offset" effect as Porter and van der Linde (1995 a; 1995 b) suggest.

By providing a focused in-depth study of a specific industry -- innovation and the regulation in the U.S. automobile industry, this research overcomes the limitation of the aggregate nature of the data often present in previous research (Jaffe et al., 2002; SQW, 2006) Furthermore, innovation in automotive emission control technologies provides a very interesting case for better understanding the how a regulated industry is impacted and responds to technology-forcing regulation. Unlike previously studied cases of CFC phase out (Ashford, Ayers & Stone, 1993) or flue gas desulfurization systems used for SO_2 control for electric power plants (Taylor et al., 2005), automotive emission control technologies represent a more complex set of technologies with a great number of upstream and downstream firms involved in the innovation process[1]. They also allow for a study that goes beyond a one time event, with an

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[1] Automotive emission control technologies consist of multiple components such as a catalyst, electronic feedback control, and thermal management systems where the development of each component itself requires a multiple number of firms supplying sub-units. For example, a catalyst system typically includes ceramic substrates, wash-coats and noble metals. The supply of material and other components requires processing such as coating and canning, which also involves multiple firms.

evolving regulatory regime with varying degrees of stringency over time.

We organized this paper as follows: it begins with a background section that discusses the impact of technology-forcing environmental regulation on innovation. Then it describes the specific theories and associated hypotheses, followed by the methods used to develop the relevant patent set and detailed descriptions of analyses used: patent, regulatory, and regression. Results of these analyses are subsequently presented. The paper concludes with a discussion of the influence of the technology-forcing type of government regulations on technological innovation. Policy implications of the principal findings and a description of future work are also provided.

TECHONOLOGY-FORCING REGULATIONS AND INNOVATION

Technology-forcing regulations belong to what have been dubbed “command-and-control” policies. Command-and-control policies are seen as an alternative to so-called “market-based” approaches, though in some instances the distinction is not always crystal clear (For a general literature on the theory of technology-forcing regulations see Crandall & Lave, 1981; Breyer, 1982; Leone, 1986; Crandall, Gruenspecht, Keeler & Lave, 1996).Command-and-control regulations set uniform standards for firms to meet, typically using two different approaches: performance-based regulations (or performance standards) and technology-based regulations (or technology standards). Performance-based regulations allow firms to meet regulatory standards or objectives using the least-costly means, whatever the technology or approach.[2] Yet, the performance levels that firms are required to meet are typically not considered to be feasible using current technologies. Technology-based standards mandate that particular technological avenues or approaches be taken to meet the objectives. When mandated, these technologies or technological pathways have not been fully developed, but experts believe that, when perfected, will achieve the regulators' goals. Technology-based standards are usually justified under circumstances where information asymmetries exist between consumers and manufactures (Leone, 1999). It would cost consumers less for regulators to require that firms adopt a specific technology or technological pathway to meet the regulatory objective than for the firms to explore and develop different options to meet those objectives. Such technology-based standards can be problematic, however, because firms have little incentive to innovate and move the technology forward from the regulatory mandate. This is may be generally true even under "best-available-technology" standards, which in theory call for firms to upgrade regularly to improved technologies because they are not generally rewarded financially for investing in R&D, innovation, and adoption of improved technologies to meet or exceed the goals established by regulators (Jaffe, Newell & Stavins, 2003).

Thus, *Technology-forcing* regulations can be implemented using either technology-based or performance-based standards; firms are forced to improve particular technologies or pursue R&D in those mandated technological pathways to the point of satisfying regulatory standards or objectives (Jaffe et al., 2002). Importantly, although both approaches can be designed to force innovation, theoretically the outcome could be entirely different. Unlike firms operating under technology-based standards, firms operating under performance-based standards have leeway in achieving the goal with any technologies available or any they might invent (and, obviously, they have adequate incentives to do so at the lowest cost to them).

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[2] However, as Robert Leone (Leone, 1999) points out, "Analysts are also aware that sometimes the practical consequence of setting a performance standard is to set a *de facto* technology standard because the performance

U.S. AUTOMOBILE EMISSION CONTROL: A CASE OF THE PERFORMANCE-BASED TECHNOLOGY-FORCING REGULATIONS

Public concerns over how automotive emissions contribute to overall levels of harmful air pollutants such as NO_x and CO eventually triggered the government to impose regulations on automobile tailpipe emissions beginning in the 1960s. The first emission control initiative, in 1961, came from the automotive industry, which voluntarily installed positive crankcase ventilation devices on all cars sold in California to reduce blow-by emissions. However, the industry did not actively seek to further develop other emissions control devices (White, 1982). To address this problem, the California legislature set up the California State Motor Vehicle Pollution Control Board in 1961 and established a driving test schedule for measuring emissions (Mondt, 2000). California's subsequent emission control standards were promulgated in 1966. Threse were satisfied by the industry through engine modifications, including evaporation control systems, air preheating by a thermal air cleaner, and spark control (Mondt, 2000).

Realizing the need to harmonize legislation at the federal level and establish a specific agency with national pollution abatement authority, Congress passed amendments to the Clean Air Act (CAAA) in 1965 and authorized the Department of Health, Education and Welfare (HEW) to set automotive emissions standards (Lave & Omenn, 1981). The HEW subsequently set new emission standards for HC and CO for 1968 model year cars and light-duty trucks.

In 1970, the CAAA meant an important new step in automobile emissions control. (A summary of the critical regulations is provided in Table 1). The newly created Environmental Protection Agency (EPA) specified 90% reductions for the levels of HC and CO emissions by 1975 when compared with 1970. It also required 90% reductions of 1971 NO_x levels by 1976 (White, 1982). These standards translated as 0.41, 3.4 and 0.4 grams per mile for HC, CO and

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requirements are based on a prototype technology. . . ."

NO_x, respectively. In response, automobile manufacturers mounted a serious opposition effort, and requirements were delayed several times. In 1973, intermediate emission standards were set for the 1975 model year. The 90% emission reduction requirement for HC was delayed until 1980, and the requirements for CO and NO_x were delayed until 1981 by the 1977 Clean Air Act Amendments (1977 CAAA) (White, 1982). The 1977 CAAA also reduced the NO_x emission requirement to 1.0 g/ mile.

[Insert Table 1 here]

No further increases in the stringency of emission reduction requirements followed until the late 1980s. California passed its own Clean Air Act in 1988, which required reductions of 1987 levels of volatile organic compounds (VOC) and NO_x by 55% and 15%, respectively (NESCAUM, 2000). Following California, Congress amended the Clean Air Act in 1990 (the 1990 CAAA), requiring reductions in the 1990 levels of HC and NO_x of 35% and 60%, respectively, by 1994 (Tier I standard) (NESCAUM, 2000). The EPA finalized even more stringent standards in 1999 to be phased in between 2004 to 2009 (Bertelsen, 2001). These “Tier II” standards are similar to California’s LEV II (Low Emission Vehicle II) program standards adopted in 1998. They require reductions in HC and CO emissions of 98% and 95%, respectively, compared to uncontrolled 1965 automobile (NESCAUM, 2000).

The National Low Emission Vehicle (NLEV) program emerged between the imposition of Tier I and Tier II standards. Its goal was to adapt California’s LEV program and apply it throughout the northeast Ozone Transport Region (EPA, 1997). Under NLEV, manufacturers had the option of complying with the program, which was more stringent than Tier I standard. Once manufacturers committed to the program, they would be required to meet the standards in the same manner as other federal emission requirements (EPA, 1997). Nevertheless, they agreed to comply with the tighter NLEV standard because the EPA agreed to provide regulatory stability and to reduce regulatory burdens on manufacturers by harmonizing federal and Californian standards (EPA, 1997). The NLEV program continued through 2003 and was replaced afterward by the Tier II program (Bertelsen, 2001). The NLEV standard required automobile manufacturers to introduce—before the 2001 nationwide vehicle introductions—cleaner vehicles to the mandated ozone transport regions according to the following schedule: 40% transition low emission vehicles (TLEV), 30% LEV, and 30% Tier I vehicles in model-year 1999 and 40% TLEV and 60% LEV in model-year 2000.

This temporal series of regulations in the history of automobile emissions control - 1970CAAA, 1977CAAA, 1990CAAA and NLEV provide a very natural industry setting to study the potential impact of technology forcing regulation on innovation. The 1970CAAA and 1990CAAA in particular, are regulations that clearly possess technology-forcing characteristics. As explained above, both amendments required standards of pollution control beyond what perceived to be the state-of -the-art emission control levels for automobiles at the time when the regulations enacted. The analyses of this article will be built around these two important technology-forcing regulations.

Technology-Forcing Regulation, Stringency and Innovation

Existing work suggests the possibility of a link between the enactment of technology forcing regulation and innovation. Industry level analyses such as those presented by Brunnermeier and Cohen (2003) and Pickman (1998) have found a positive relationship between innovation in environmental technologies and pollution abatement expenditures. Moreover, firm level work in particular industries seems to be finding results consistent with the aggregate perspective. First, Roediger-Schluga's (2003) perceptual study on the techno-economic consequences of the Austrian Volatile Organic Compounds (VOC) emission standards notes that that firms reported to have accelerated the rate of product innovation and have broadened their product range as a result of R&D devoted to compliance with regulation. Second and perhaps of greater direct relevance to this study, Taylor et al. (2003) and Popp (2002) show that the stringent New Source Performance Standards (NSPS), which mandated dramatic improvements in SO_2 removal efficiency from fissile fuel-fired steam boilers, stimulated innovation that led to the development of more cost effective flue gas desulfurization units (scrubbers) for SO_2 control. These two studies represent cases where the technology-forcing regulation stimulated innovation. Yet, the NSPS exemplify the case of technology- forcing regulation which targeted specific technological solution to meet desired regulatory standards. Nevertheless, their findings, together with the empirical results discussed above lead to our first hypothesis:

> *Hypothesis 1a: Regulatory standards mandated under the performance-based technology-forcing regulations stimulate innovation*

When enacting technology-forcing performance based regulation, stringency is seen as one of the critical instruments used by policymakers to influence the general environment for innovation (Ashford et al., 1993) . Thus, in this research, we are also interested in examining whether firms' innovative activities are indeed associated with varying degrees of stringency of relevant performance-based technology-forcing (PBTF) regulations. Recent theoretical studies by Greaker (2006) and Fees and Muehlheusser (2002) argue that stringent regulatory standards could make regulation-driven innovation possible by enlarging a market for new pollution abatement equipment for firms in the upstream service sector for pollution control devices.

Furthermore, Mohr (2002) claimed that regulatory pressures that promote the use of new technologies not only alleviates the pollution but also improve productivity. Mohr's study strongly suggests that tough regulatory pressures stimulate innovation and induce endogenous technical change leads to the development of cleaner and more efficient new technologies.

But according to Ashfold et al. (1993), high regulatory stringencies such as those that can be found in the technology-forcing regulation could also work as an innovation deterrent. Firms under stringent technology-forcing regulation may find it risky to invest in developing a new technological system because the technology that they develop may fail to become a dominant model among competing designs or become unnecessarily too costly (Ashford et al., 1993).

Nevertheless, since several empirical (e.g., Brunnermeier and Cohen 2003; Pickman 1998) and theoretical studies (e.g., Greaker 2006: Moore 2002) have suggested the possibility for significant linkage between regulatory stringency and environmental innovation, we hypothesize:

> *Hypothesis 1b: More stringent PBTF regulatory standards would induce relatively higher levels of innovation compared to the levels driven by less stringent PBTF regulatory standards*

Technology-Forcing Regulation and Responses from Industrial Sector

An important dimension of Porter's hypothesis is that regulations reduce uncertainty in firms' decisions to invest in novel technologies (Porter, 1991). The idea is that, although regulations may impose additional costs on regulated firms, the industry may benefit if regulations create business opportunities through innovation that can offset the extra costs of meetings the imposed standards (Esty, 1994). In particular, strategic environmental management literature embrace the notion that firms may attain a competitive advantage from environmental performance in their response to calls for environmental protection (Shrivastava, 1995; Klassen

& McLaughlin, 1996; Nehrt, 1996; Russo & Fouts, 1997; Aragon-Correa, 1998; Sharma & Vredenburg, 1998; Klassen & Whybark, 1999; Sharma, Pablo & Vredenburg, 1999; Christmann, 2000). These studies base their theoretical grounding on the resource-based view of the firm (Hart, 1995), suggesting that a proactive strategy, such as implementation of pollution prevention technologies into business practices (Shrivastava, 1995; Nehrt, 1996; Russo & Fouts, 1997; Aragon-Correa, 1998; Klassen & Whybark, 1999), or environmental management best practices (Hart, 1995; Christmann, 2000) can lead to a competitive advantage.

Thus, technology-forcing regulation, which mandates introduction of a technological solution capable of achieving higher performance, provides substantial incentives for regulated firms to invest in R&D and to innovate. Moreover, firms subject to technology-forcing regulation could find opportunities to gain competitive advantage over rival firms if they could incorporate technologies that respond to the regulation standard earlier than their rival firms, or with superior performance (or lower cost).

The enactment of PBTF regulations induces creation of new market for advanced technologies. Thus, it is possible that profit incentives created by the passage of the regulations can also attract firms to enter regulated induced market for technology and caused entrant firms to innovate. As Schmookler (1966) already notes in his seminal work, “the amount of invention is governed by the extent of the market” In fact, recent work on regulatory economics in the pharmaceutical industry (Lichtenberg & Waldfogel, 2003a; Finkelstein, 2004) provide evidence that market incentives embedded in the passage of regulations led to increases in product innovation and firm entry. The Orphan Drug Act in 1983 which was enacted to give pharmaceutical firms special incentives to develop drugs for diseases affecting fewer than 200,000 Americans had spurred drug developments for small populations (Lichtenberg &

Waldfogel, 2003b). Finkelstein (2004) also found robust evidence of increase in new vaccine clinical trials when the Center for Disease Control and the Medicare adopted policies that could increase the expected returns to developing vaccines.

In case of environmental regulations associated to automobile emissions considered in this study, firms that respond to the policy belong to either the regulated auto assemblers or the pollution control industry (Ashford et al., 1993). Firms from other industrial sectors that belong to neither the regulated nor the pollution control industry may also enter the market if regulations provide profit incentives for them to enter into upstream pollution abatement service sector (Greaker 2006; Ashford et al., 1993). Thus we hypothesize that:

> *Hypothesis 2: Technology-forcing regulation can induce innovation from firms that are directly conditioned by the regulation, as well as firms that operate in* upstream pollution abatement service sector or the pollution control industry.

Competitiveness and Technology-Forcing Regulations

The conventional wisdom toward the impact of environmental regulation on competitiveness is that it harms domestic firms’ competitiveness in international markets by imposing significant costs (Jaffe et al., 1995). However, as explained above, Michael E. Porter advanced an opposing view, suggesting that environmental regulation may actually help firms become more competitive (Porter & van der Linde, 1995b; Porter & van der Linde, 1995a) As regulations place constraints on firm activities, they are likely to explore new ideas and acquire new competences and technologies, which can facilitate the process of compliance with regulatory stringency (Jaffe & Palmer, 1997). But the Porter hypothesis also implies that strict environmental regulation could give domestic firms competitive advantage over foreign firms

(Porter & van der Linde, 1995b; Porter & van der Linde, 1995a). Domestic firms under demanding stringent regulations may be able to acquire competences earlier than firms operating in foreign market and thus become more competitive over foreign firms operating in other market as other jurisdictions follow more stringent regulatory trend. This idea that domestic firms may benefit from stringent regulation was explored by Rugman and Verke (1998). They use a theoretical framework to reflect on the potential linkage between environmental regulations and the strategies of multinational enterprises, concluding that the Porter hypothesis is only feasible for countries that have large domestic markets where governments have substantial power on international regulation trends. Considering the fact that U.S. satisfies both of the Rugman and Verke's criteria for the realization of the Porter hypothesis; we hypothesize as below:

> *Hypothesis 3: U.S. technology-forcing regulations would lead U.S. firms become more innovative, compared to foreign competing firms operating in the U.S.*

METHODS

Data

Expenditure Estimates. We used cost estimates for automobile emission control devices as the compliance cost data. Cost data itself came from number of different sources that include the EPA (1990) and the California Air Resource Board (CARB, 1996).

The EPA's (1990) study provides aggregated capital cost estimates for emissions control devices from 1972-1993[3] that include: evaporative emissions canisters from the model year 1972,

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[3] The EPA's 1990 study reports that device costs remain constant after 1984. This research assumes that the costs of devices remain constant until the phase-in of the more stringent Tier 1 standards in 1994. We further assume that

high altitude emissions controls from year 1984, catalytic converter beginning year 1975, exhaust gas recirculation units for years 1973-1974, and air pump units for years 1970-1974 (EPA, 1990; McConnell, Walls & Harrington, 1995). Analytical procedures and assumptions used for calculations can be found at McConnell et al.'s "Resources for the Future Discussion Paper" (McConnell et al. 1995).[4]

Notable increases in device costs were associated with the 1975 introduction of oxidation catalysts to satisfy intermediate emission standards. Likewise, steep increases in cost were also found around the introduction of the more advanced three-way catalysts with electronic loop control in 1981. The EPA's 1990 study reveals that it costs approximately an additional $746.3 per vehicle to achieve 90% of tailpipe emissions reductions from *pre* 1970 emission level. Further study by the EPA using the data from the U.S. Bureau of Labor Statistics shows that the cost of emission control systems further increased due to the phase-in of the Tier I standards in 1994 (Anderson & Sherwood, 2002). The Tier I standards which were phased in 1994 as a result of the enactment of the Amendments of the Clean Air Act in 1990 created additional vehicle costs of approximately $97.2 (Anderson & Sherwood, 2002).

Patent Database. We use successfully applied patent count as a measure of innovation activities. We recognize that they are traditionally known an imperfect measure of innovative outputs (Griliches, 1990; Archibugi & Pianta, 1996; Lanjouw, Pakes & Putnam, 1998). For example, not all inventions or innovation are patented, and quality of individual patents varies quite widely (Lanjouw et al., 1998; Popp, 2005). Thus, Popp (2005 pg. 214) argued argues that results of patent based research should, thus, be interpreted "as the effect of an 'average' patent,

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device costs remain the same from 1970 to 1972 due to the fact that a new technology, the oxidation type catalyst converter, first appeared in 1975.

[4] McConnell et al's study incorporates *the Survey of Current Business* by the Bureau of Economic Analysis (BEA), study by White (1982), Crandall, et al. (1996), and Wang et al. (Wang, Kling & Sperling, 1993).

rather than any specific invention." Nevertheless, patent statistics have been extensively used by academics studying technological changes (e.g. Jaffe & Palmer, 1997; Trajtenberg, 2001; Popp, 2002; Popp, 2006). One of the biggest advantages of using patent data is that it offers an abundant quality of available data with organizational and technical details (Lanjouw et al., 1998). In addition, patent data allows construction of a time series database (Popp, 2003).

We developed a relevant patent set using patent data from the U.S. Patent and Trademark Office (USPTO). We adopted an abstract-based keyword search method in addition to using the conventional patent class-based search. Our purpose in adopting an abstract-based keyword search is to strengthen the representativeness of our patent database in automobile emissions control technologies. Patent classifications tend to reflect the technological nature of the inventions; and thus, any complex technological system which possesses multiple subsystems, such as automobile emissions control technologies, are likely to belong to multiple patent classifications. Consequently, relying on patent classifications alone may run the risk of creating a patent database that contains patents that belong to the searched patent class but are not necessarily related to the technological system of interests. For example, an inventor may patent his or her invention to be a catalyst for pollution control that is specifically designed for an electric power plant, but that particular patent may belong to the same patent class as other catalyst patents invented for automobile applications. For a very similar reason, relevant patents of interests may also belong to other patent classes not captured by a researcher. An abstract-based keyword search allows researchers to double-check their search findings with a patent class-based search approach; it also enables researchers to identify any potential relevant patents not found under class-based search.

We selected seven different keywords for an abstract-based keyword search: catalytic converter, emission, automobile, catalysts, pollution, exhausts, and engine. These keywords were then permutated to search the U.S patent database electronically, yielding a preliminary set of potentially relevant patents. We eliminated duplicate patents, and screened for relevant patents by reading abstracts of searched patents. Sometimes it was necessary to examine the “Assignee” and “Claims” portions of the patent because catalytic converter technologies can be related to non-automobile technologies. For the class-based search, we adopted patent subclasses that represent catalytic converter technologies from prior patent studies on catalytic converter technology (Campbell & Levine, 1984). The process for obtaining relevant patents using class-based searching was similar to that of an abstract-based keyword search. We used patent application date rather than patent grant date to closely reflect timing of inventors’ propensity to patent to and avoid vagaries involved in patent grant processes (Griliches, 1990).

We identified a total of 2,098 successfully applied automotive emissions control patents by firms for the period between 1970 and 1998. Major USPC classes and subclasses representing automotive emissions control technologies found are listed in Table 1.

[Insert Table 1 here]

Figure 1 contrasts a time-series with the magnitudes of patenting activities that have the same series of stringency levels for each of three major pollutants. Patenting of automotive emissions control increased significantly in the early 1970s and then started to decline from the mid 1970s. The level of patenting activity remained low—below fifty patents per year—until the late 1980s, when it started to increase again, continuing into the 1990s.

[Insert Figure 1 here]

This paper aims to examine any potential statistical connections between innovation activities and the regulatory stringencies embedded in the series of technology-forcing regulations. We attempt to glean new insights from regression results regarding firms' innovative behaviors under regulatory pressures, and the effectiveness of technology-forcing policy instruments on stimulating technological change.

Variables

Dependent variables. To test whether firms' overall innovative activities are associated with the onset of technology-forcing standards (*Hypothesis 1a &1b*), we use firms' successful U.S. patent application counts as a dependent variable, *FirmsPatents*. Patent filing dates instead of patent grant dates are used to remove any potential uncontrolled variance from the patent – granting process. We are also interested in examining potential differences in collective responses to regulatory forces by regulated firms and other industry players (*Hypothesis 2*). Thus, we categorize the patents as belonging to auto assemblers as well as industry suppliers, creating two subsets of patent applications as dependent variables: *AssemblersPatents* and *SuppliersPatents.*

To investigate whether U.S. technology-forcing regulations in automobile emissions control leads U.S. firms to become more innovative compared to foreign firms in the U.S. market (*Hypothesis 3*), we also create a subgroup of patents associated to the top U.S. firms —General Motors, Ford Motor Company, Engelhard, W.R. Grace, Corning, and Universal Oil Production Company— as a dependent variable, *USpatents.*

Independent variables. We use EPA's (1990) and the California Air Resource Board's (CARB 1996) cost estimates for automobile emission control devices as a measure for regulatory stringency, *Expenditure*. According to Jaffe and Palmer (1997), EPA's regulatory impact analysis (RIA) provides estimates of regulatory costs to industry, and this estimate may provide a better measure of aggregate environmental regulatory stringency. We do not use the Pollution Abatement Cost and Expenditure (PACE) survey data conducted by the Census Bureau of the U.S. Department of Commerce primarily because that the PACE data is known to be inadequate in capturing the effect of regulatory burden on the *performance* of consumer products such as emission control devices (Jaffe and Palmer 1997). In general, firms under performance type technology-forcing regulations encounter severe technological uncertainties and risk, since firms not only need to determine paths for subsequent technological change, but also are required to develop stable technological systems in a timeframe that mandated through regulations. The steady increase in EPA's estimated capital expenditures in the 1970s and 1990s properly reflects succession of more stringent regulatory standards that mandated installation of more advanced emission control devices.[5]

The variable, *MarketShareAssembler*, represent assemblers' market share in the U.S. This variable is used to examine potential impact that competitive market pressures have on firms' propensity to patent in the U.S. auto market during the period of the study. We use Ward's Automotive Yearbooks to estimate automakers' market shares in the U.S.

The variable*, ForeignPatents* represents successful U.S. patent applications by foreign firms. The use of this variable follows the model proposed by Jaffe and Palmer (1997). As they explain, its inclusion works in two dimensions. First, factors that influence U.S. firms' patenting incentives may affect patenting activities by foreign firms differently. Thus, their inclusion as an independent variable will control for that potential differential. More importantly, this variable

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[5] We believe that the EPA's cost analysis properly captures cost trends for required core components for automobile emission control devices. Nevertheless, we suspect that the EPA's estimates may not represent the *true complete regulatory burden* for firms under auto-emission standards that are designed to "force" technological innovation. Successful development and installation of complex automobile technological systems such as auto-emissions control devices tend to require R&D efforts beyond development of key components (Brusoni, Prencipe & Pavitt, 2001). Likely R&D investments towards integrating key components and technological modules into existing engine exhaust structures may not have been properly captured in the EPA's estimates.

will enable us to test *hypothesis 3* because we can examine whether U.S. firms' patenting activities are significantly associated with the compliance expenditure variables, controlling for the rate of patenting by their foreign rival firms in automobile emission control technologies also under the U.S. regulations (Jaffe and Palmer 1997). .

To ensure that results obtained for patenting activities in emissions control technologies are not just a reflection of an overall trend in innovations in automotive technologies, we include the total innovation activity in automotive technologies in the equation as a control variable, *TotalAutoPatents*. We used the United States Patent Classification (USPC) index to estimate overall patenting activity in automotive technologies. Subclasses listed under "Automobile" in the USPC index and Class 180 (Motor Vehicles) were selected, and patents applied under these subclasses were counted from 1970 to 1998.

Statistical Model

We use a negative binomial specification to quantitatively analyze the impact of regulation on innovation. A negative binomial model can account for the count nature of the patent data, a well as for the repeated time series cross-sectional observations (Hausman, Hall & Griliches, 1984). We employ both pooled and firm fixed effect models to build robustness into analysis. Firm fixed effect (μ_i) is included to account for unobservable factors that are associated with firms. Firms may have different capabilities and strategies in terms of technological investments, and firms' patent strategies may also differ depending on their R&D intensities (Arundel & Kabla, 1998). Firms from different countries may have different propensity levels to patent (Pavitt, 1985). Inclusion of firm fixed effect addresses biases from these firm heterogeneities. When considering firm fixed effects, we use aggregated patent counts of top fifteen patenting firms that include five automakers--Toyota, Ford, General Motors, Nissan and Honda, and ten component suppliers -- Engelhard, W.R. Grace, Corning, Nippondenso, EMITEC GmbH, NGK insulators, Robert Bosch, Universal Oil Production Company, Hitachi, and SIEMENS.

Specifically, the conditional mean of the fixed effect model is as follows:

$$\begin{aligned}&E(y_{it} \mid App_T, Expenditure_{t-\tau}, X_{it}, Z_t)\\&= \exp\{\sum_T \alpha_T App_T + \beta_T (App_T * Expenditure_{t-\tau}) + \delta_T X_{it} + \lambda_T Z_t + \mu_i\}\end{aligned}$$

where y_{it} are the patents applied for by firm *i* in year *t*, X_{it} represent explanatory variables that vary in both time and firms such as automaker's market share in the U.S. (*MarketShareAssemblers*); Z_t represent *v*ariables that are stable across firms but not across time such as total number of successful patent applications in auto technologies (*TotalAutoPatents*), and successful U.S. patent applications by foreign firms (*ForeignFirms*). App_T represents an aggregated dummy variable that, instead of changing every year, is equal 1 for all patents that were applied in period *T*. This approach allows us to still control for shocks to the system across critical time periods, while allowing a greater number of degrees of freedom in the regression and reducing yearly noise. For our study, we considered seven groups for application years 70-73, 74-77, 78-81, 82-85, 86-89, 90-93 and 94-98 respectively.[6]

A key feature of the model is that we represent the impact of regulatory stringency through a series of interaction terms, $App_T * Expenditure_{T-\tau}$, instead of a single regulatory compliance cost variable ($Expenditure_{T-\tau}$) . A single regulatory compliance cost variable would capture the average impact of cost of compliance on innovation over the entire period of study.

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[6] Please refer to Table 2 for detailed explanation on different regulations in automobile emissions control in the 1970s and the 1990s

But regulations were imposed mainly in the 1970s and the 1990s and the period from 1982 to 1989 is free from any regulatory forces. Thus the interaction terms, App_T * $Expenditure_{T\text{-}\tau}$ help us examine potential impact of different policy regime implicit under different periods.

We also include two different forms of the lagged expenditure variable: a single year lagged expenditure and a moving average of the prior three years (MAP3) to address firms' tendency to invest in R&D prior to the phase-in regulatory stringency. Firms especially in the auto industry are known to have a long product lead time (Clark & Fujimoto, 1991).

Hypotheses are tested by mainly examining the significance of interaction terms between the expenditure and the various *T* periods for the full patent sample (*Hypothesis 1a & 1b*), assemblers' and suppliers' patent sub-samples (*Hypothesis 2*) and the US firms' patent sample (*Hypothesis 3*).

RESULTS

Table 3 provides descriptive statistics and inter-correlations among variables used in the study. We first begin our discussion by examining the significance of key explanatory variables. We then separately examine and compare regression results of assemblers and suppliers' patent sets with those of the full sample patent set. Finally, we analyze regression results for the patent set drawn from U.S. firms to determine whether federal technology-forcing regulatory regimes for automobile emission control technologies caused higher patenting rates for domestic U.S. firms after controlling for the rate of foreign patenting.

[Insert Table 3 here]

Induced Technological Change in Automobile Emissions Control, Overall Picture

Results of a cross-sectional time series negative binomial regression models for the full patent sample and fixed effects for the top 15 firms are shown in Table 4.

[Insert Table 4 here]

We find that in the full patent sample (Table 4), the lagged compliance cost variables are significant during the periods 7073 and 9093 ($Expenditure_{7073-\tau}$ *and* $Expenditure_{9093-\tau}$) in both the pooled and fixed effect models; this finding persists with MAP3 lagged expenditure models[7]. These results provide evidence that regulatory pressures under the technology-forcing CAAA1970 and CAAA1990 regulations induced innovation in automobile emissions control technology, supporting *Hypothesis 1a* that the technology-forcing performance based regulation can stimulate innovation. It is not surprising to observe that lagged compliance cost variables in the early 1970s and 1990s are positive and significant. As explained before, the 1970 CAAA and 1990 CAAA were the critical stringency regulatory mandates, with the remaining periods either associated to delays in the enactment of the regulation, or no change at all in the mandates.

Moreover, according to the *hypothesis 1b,* the impact of the 1970CAAA on innovation should be stronger than that of the 1990CAAA. The 1970 CAAA called for 90% reductions in automobile emissions from the 1970 levels of HC, CO and NO_x emissions, while the 1990 CAAA mandated short term lowering of both HC and NO_x by 39% and long term lowering of HC by 70%, CO by 50% and NO_x by 80% relative to the 1990 level. Indeed, in the regression results of Table 4 the coefficient on the lagged compliance cost variable during the period 7073 ($Expenditure_{7073-\tau}$) is greater than that of the period 9093 ($Expenditure_{9093-\tau}$)

Interestingly, the coefficient on $Expenditure_{7881-\tau}$ is negative and weakly significant, This finding is apparently rather surprising since regulatory stringencies continued to increase until 1981. Yet, one has to remember that the 1977CAAA delayed the imposition of the 90%

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[7] The variable expenditure does not appear without an interaction because we are interacting it with the full set of periods, even the omitted one (70-73). This allows a more direct comparison across periods.

emissions reduction requirements, which may explain the reduced intensity of innovative activities. In fact, consistent with this perspective, we observe a reduction in patenting activity from 1975 to 1981 (see figure 1). It is possible that the industry had already developed three-way catalysts (TWC) technologies to meet the more stringent terms of the 1970CAA by mid-1970s, before the passage of the 1977CAAA, but believed strongly it could not be perfected in time to meet the original schedule .(Lee, Veloso, Hounshell & Rubin, 2004)

Finally, coefficients reported in the tables show that the total automotive patenting variable is not significant; suggesting that patenting in automobile emission control does not necessarily reflects overall patenting in automotive technologies during the same periods.

Automakers and Suppliers' Differential Propensity to Innovate

Tables 5 and 6 show regression results for assemblers and suppliers' patent samples. Similar to what is observed using the full patent sample (Table 4), the lagged compliance cost variables in both the pooled and fixed effect models are significant for the periods 7073 and 9093, suggesting that both automakers and component suppliers responded to regulatory pressures due to the 1970 CAAA and the 1990 CAAA. These results support *Hypotheses 2,* which predicted that technology-forcing regulation induces innovation in both directly regulated firms and firms in the upstream pollution abatement service sector or pollution control industry.

[Insert Table 5 & 6 here]

The finding that auto assemblers responded to technology – forcing regulation through a variety of competing innovative activity goes beyond patents and is consistent with historical accounts of the development of the automobile emission control technologies. In 1975, Honda introduced CVCC engines and Chrysler introduced lean-burn engines in their attempt to differentiate themselves from other automakers that adopted catalytic converter technology to meet the 1975 intermediate automobile emission standards (Dexter, 1979; Doyle, 2000). Even among auto assemblers that followed the strategy of satisfying mandated environmental standards using the catalytic converters had important differences in technology: Ford pursued the monolithic type converter while the GM developed pelleted type converter; these had fundamental design differences in the key catalyst substrate (Mondt, 2000).

Regression results also confirm that the technology-forcing regulations have significant influence on pollution abatement equipment firms. Regulations create demand for pollution abatement equipment and thus attract entry into this newly created or enlarged market for pollution abatement equipment (Greaker, 2006). This in turn creates fertile environments for innovation, especially when regulation stringencies require installation of new products whose performance levels are not considered as technological feasible by current knowledge.

We also find the regression coefficient for the market share of assemblers (*MarketShareAssemblers*) is positive and significant (see Table 5). This suggests that firms with higher market shares tend to be comparatively more innovative than those with weaker market presence. Our finding are consistent with Schumpeter’s (1942) argument that, the amount of R&D and innovation that regulated firms perform depends on the size of the market they capture.

Technology-Forcing Regulations and the Porter Hypothesis

Table 7 shows the result of regressions using the top six U.S. firms’ patent samples. In this regression using U.S. firms’ patent sample, we also included patenting activities by foreign firms (*ForeignPatents*) as an additional control variable. This variable enables us to examine whether U.S. firms’ patenting activities are associated with compliance expenditure, controlling for the rate of patenting by foreign firms. In doing so, we seek to test the *hypothesis 3* that claims that U.S. regulation causes U.S. firms become comparatively more innovative than their foreign rival firms (Porter and van der Linde, 1995; Jaffe and Palmer, 1997).

[Insert Table 7 here]

As shown in Table 7, the coefficients for regulatory expenditures during the periods of the early 1970s and 1990s ($Expenditure_{7073-\tau}$ *and* $Expenditure_{9093-\tau}$) are positive and significantly related to patenting activities by U.S. firms in the base regressions (model 1 & model 4). When foreign patenting activity is included in the equation as an additional control variable, the coefficient on the $Expenditure_{9093-\tau}$ variable becomes insignificant. These findings suggest that the technology-forcing auto emissions regulations caused U.S. firms comparatively more innovative than foreign rival firms, yet such “innovation offsets” effects occur only to a limited extend prior to 1975. Only the 1970 CAAA regime seems to be related to “innovation offset” for U.S. firms. Negative regression coefficients in the 7477 and 7881 periods seem to indicate that overall decline in patenting activities in the mid to late 1970s (Figure 1) also account for a general trend in U.S. firms’ patenting activities during same period.

The regression results offer partial support to *hypothesis 3* that U.S. technology-forcing regulations lead U.S. firms become more innovative compared to foreign competing firms. Consequently, equivalent partial support is offered to the Porter’s hypothesis that the innovation-offset effect of stringent regulations would make U.S. firms more capable than their foreign rival firms. These results seem to have happened in the early stages of the regulations, when the regulatory performance standard was one of the most stringent and leading regulatory standard around the globe (Faiz, Weaver & Walsh, 1996).

The idea that innovation offsets tend to occur more strongly in the early phase of market creation has been discussed by previous theoretical work in environmental policy and management literature. For example, Feess and Muehlheusser's work (2002) suggests that the realization of the Porter hypothesis through gains from learning in the pollution abatement equipment industry would be likely in an infant environmental industry. Similarly, Greaker (2006) shows that stringent regulations have an higher upstream price effect for new pollution abatement equipment, and its effect are likely to be higher when a well-established market for equipment does not exist yet. Our empirical findings lend support to these theoretical works, providing a key starting base for understanding the complex inter-relationship between innovation offsets, timing and stringency of the regulations, and the overall market environment.

DISCUSSION AND CONCLUSIONS

Lee Iacocca and other industry executives asserted that the 90% emissions reduction requirement "could prevent continued production of automobiles" and "do irreparable damage to the American economy" (Weisskopf, 1990). However, after 30 years of regulatory actions, all new cars today are equipped with emission control devices capable of reducing CO, HC, and $NO_{x.}$ by more than 95% (Bertelsen, 2001).

In this paper, we present empirical evidence that technology-forcing regulations imposed on the automobile industry stimulated innovation in automakers and suppliers. Our models show that technology-forcing regulation designed to control automobile emissions was effective in inducing innovation. In particular, the strong increases in regulatory stringency during the early 1970s and 1990s were associated with the significant increases in innovation activities as measured by patenting activities,. This systematic pattern remains robust throughout models with different specifications.

Our study offers new insights regarding the relationship between performance-based regulatory standards and the industry's innovative responses. First and more directly, it shows that command-and-control (CAC) type regulations can be an important driver of innovative activity. Taylor, Rubin et al. (2005) as well as Popp (2003) had already presented empirical evidence linking CAC regulation to innovative activity for the case of SO_2 control. Yet, their studies looked at *technology-based* CAC regulation. Our work complements and reinforces the findings of prior research.. But, more importantly, it shows for the first time the existence of a linkage between technology-forcing regulation based on *performance standards* and innovation..

Second, the observation that the strongest innovative reaction happened when the government enacted the two most ambitious regulatory requirements, suggests that stringency is a key determinant of the degree of induced technological change (Ashford et al., 1993). In fact, historical observations indicate that the regulatory stringency of the 70s forced the auto industry to abandon a prior approach of using engine modifications to respond to environmental pressures and instead pursue catalytic converter technology to reach compliance. This suggests that high levels of stringency may actually drive the direction of technological innovation. Yet, our understanding of how radical technologies compete and get selected among competing options within regulatory environments is limited. Future studies could perhaps examine potential connections between regulatory stringency and the selection mechanisms among variety of competing technological options.

Third, our finding that the U.S. auto-emissions regulations (during the 1970 CAAA regime) correlate significantly with U.S. firms' innovative activities after controlling for foreign patenting provides supporting evidence for the Porter hypothesis. In other words, U.S. auto-emissions standards caused U.S. firms to become comparatively more innovative than foreign competitors. However, we do not know whether increased firms' R&D activities in response to regulatory pressures came at the expense of other R&D programs. Yet, since performance-based auto-emissions standards are outcome-oriented regulations, we can nevertheless claim that our study supports a "narrow" version of the Porter hypothesis, that is, "certain types of environmental regulation stimulate innovation (Jaffe & Palmer 1997, pg. 601)."

Lastly, our results suggest that performance-based CAC regulations can be a useful regulatory tool to induce more *radical* technological change, rather than incremental innovation. Prior theoretical studies that compared the effectiveness of regulatory tools and R&D incentives favor market-based approaches for providing incentives for environmental R&D (e.g. Jung et al., 1996; Requate & Unold, 2003). However, since radical innovations tend to be more competence-destroying for incumbent firms, radical technologies tend to be difficult to introduce, even if clear incentives for their adoption exist (Tushman & Anderson, 1986). Incumbent firms' reluctance in adopting radical technologies is clearly manifested in the history of automobile emissions control regulation. Initially, automakers were unwilling to adopt radical add-in type catalytic converters, and instead actively work on modifying existing engine components with the aim of reducing tailpipe emissions (Mondt, 2000). The stringency of the automobile emission control regulations, especially the requirement for NO_x to be controlled at less than 1.0 gram per mile, eventually forced automakers to surrender their initial approach and adopt radical catalytic converter technology (Lee, 2005). A similar case happened as a response to regulatory forces resulting from a California's regulatory initiative. (Schot, Hoogma & Elzen, 1994). Meeting the standards led to the development of low-emission vehicles (LEVs) and zero-emission vehicles (ZEVs). Since ZEV technologies require a fundamentally different drive-train mechanism from conventional internal combustion engine type vehicles, this represents another case of a competence-destroying radical technological change introduced in the market.

Our findings also provide new insights to the natural-resource-based view of the firm (Hart 1995; Russo and Fouts 1997; Klassen and Whybark 1998). According to this view, competitive advantage established by investing in environmental technologies tends to occur when firms implement pollution prevention technologies rather than pollution control technologies.[8] This perspective stems from the notion that implementing pollution prevention technologies relies more heavily on organizational and knowledge-based resources when compared to pollution control technologies, which are associated to the installation of end-of-pipe pollution control devices. As a result, firms can expect greater competitive advantage stemming from their investments in pollution prevention technologies. Our work shows that such perspective is based on a particular premise that may not be always general. We believe that existing perspectives on the natural-resource-based view of the firm are particularly helpful when looking at incremental evolution within the firm. Yet, as noted above, when the required change is far beyond existing technologies and perhaps threatens existing competences, it is much harder for the firm to enact this change. In these contexts, the existing the natural-resource-based view framework has less to offer in terms guidance. As our results demonstrate, both automakers and component supplies introduced rather novel systems that resulted from important knowledge investment and with a large impact in internal organizational dynamics (Lee & Veloso, forthcoming). This demonstrates that firms’ investment in pollution control technologies may equally help firm establish competitive advantage. Yet, change happened because of the presence of the CAC regulation. These observation suggest that the natural-resource-based view of the

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[8] Pollution prevention technologies are defined as structural investments in operations that are designed to reduce or prevent emissions (and effluents) through fundamental changes to primary process such as material substitution or process innovation; whereas pollution control technologies represent pollution-control equipments that dispose harmful pollutants at the end of a manufacturing process (Klassen and Whybark 1998; Hart 1995) .

firm (e.g. Hart 1995) needs to be expanded. On the one hand it is important to integrate the perspective of radical vs. incremental change and their link to firm inertia. On the other, it needs to expand the role of regulation beyond roles of legitimacy and stakeholder influence and consider it also as a potential driver of radical change.

This expanded perspective has direct and consistent links to existing predictions. For example, one can have equivalent insight in what regards domestic firms' proactive strategies under regulatory environment. Existing notions show that firms with proactive strategies towards environmental issues tend to invest early in new pollution prevention technologies to gain competitive advantages over their rivals. Their expectation is that they may benefit from proprietary cost-reducing or sales-enhancing technologies developed before competitors (Shrivastava, 1995; Nehrt, 1996; Russo & Fouts, 1997; Aragon-Correa, 1998; Klassen & Whybark, 1999). But a similar perspective exists when braced with the challenge of developing radically new technologies. Our results show that domestic U.S. firms' patenting activities were significantly related with the technology-forcing regulation after controlling for foreign patenting activities. By reacting proactively in the early phase, domestic firms may exercise greater influence on the choice or the design characteristics of pollution control technology; thereby establish competitive advantage over rival firms. Following the stream of research in environmental strategy, an extension of this paper that examines in detail how suppliers' existing capability, their decisions to diversify (or new entry) into upstream equipment industry sector for regulated auto industry and their performance would be of great interest and would provide the necessary empirical evidence to fully expand existing perspective on the natural-resource-based view of the firm.

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TABLE 1
U.S. Classes and Subclasses for Automobile Emissions Control Technology Patents

USPC Class/Subclasses	Definition of USPC Class/Subclasses
60/274, 276-278	Class 60, “Power Plants,” includes the subclasses representing “Internal combustion engine with treatment or handling of exhaust gas”
422/174, 179-180	Class 422, “Chemical apparatus and process for disinfecting, deodorizing, preserving, or sterilizing,” includes the subclasses which describes apparatus, the chemical reactor, supporting catalytic processes for waste gases such as NO_x and CO.
423/213.2, 213.5, 213.7	Class 423, “Chemistry of inorganic compounds,” includes subclasses which represents utilizing the transition elements as catalyst to treat exhaust from internal-combustion engine
502/302-304	Class 502, “Catalyst, solid sorbent, or support therefore: product or process making,” includes subclasses that represents catalysts comprising lanthanide series metals or transition metals.
428/116	Class 428, “Stock materials or miscellaneous articles,” include subclasses representing a honeycomb-like structural body for catalytic converters.
73/116, 117.3, 118.1	Class 73, “Measuring and testing,” includes subclasses representing testing of motor, engine and auxiliary units such as catalytic converter to ensure optimal operations.
29/890	Class 29, “Metal working,” include subclass representing catalytic device making

TABLE 2
Government Actions with Potential Impacts on Patenting Activities

Government Actions	Enactment Date	Summary
1970 Clean Air Act (1970 CAA)	December 1970	1. The Act called for 90 percent reductions in automotive emissions (0.41 g/mi for HC, 3.4 g/mi for CO for new automobiles in 1975, which was later revised in 1974). 2. The NO_x emission standard was set at 0.41 to be met by 1976, which was later revised in 1977.
1977 Clean Air Act Amendment (1977 CAAA)	August 1977	1. Congress delayed the HC standard until 1980, and the CO and NO_x standards to 1981. 2. The 1981 NO_x standard was relaxed to 1 g/mi.
1990 Clean Air Act Amendment (1990 CAAA)	November 1990	1. Congress required further reductions in HC, CO, NO_x and particulate emissions. 2. The amendments introduced a comprehensive set of programs aimed at; more stringent emission testing procedures; expanded I/M programs; new vehicles technologies and clean fuel programs; transportation management provisions; and possible regulations of emissions from non-road vehicles.
National Low Emission Vehicle Program (NLEV)	June 1997	1. The program is designed to adopt more stringent California LEV program nationwide, started initially with northeast ozone transport regions. 1999: 40% TLEV, 30% LEV, 30% TIER 1 2000: 40% TLEV, 60% LEV 2001: LEV standard 2. Manufacturers have the option of not complying to NLEV program yet manufacturers have agreed to comply to this program as EPA and the states indicated that they provide manufacturers with regulatory stability. 3. NLEV is enforceable once manufacturers are committed to the program. 4. NLEV continues through MY2003, after which it will be replaced by Tier 2 standard.

Tier 1: 0.25g/mi HC, 3.4g/mi CO, 0.4g/mi NO_x
TLEV (Transitional Low Emission Vehicle): 0.125 g/mi NMOG, 3.4 g/mi CO, 0.4 g/mi NOx
LEV (Low Emission Vehicle): 0.075g/mi NMOG, 3.4g/mi CO, 0.2g/mi NO_x
Source: (EPA 1997; Mondt 2000)

TABLE 3
Descriptive Statistics and Correlations [a]

	Variables	Descriptions	Mean	S.D.	1	2	3	4	5	6	7
1.	*FirmsPatents*	Successful U.S. patent applications	67.97	5494							
2.	*Expenditure* [b]	Pollution control expenditures as measured by costs of automobile emission control devise	5.61	1.57	.38*						
3.	*TotalAutoPatents*	Total number of successful patent applications in automotive technologies	998.65	338.24	.80*	.57*					
4.	*AssemblersPatents*	Successful U.S patent applications by automaker	30.77	28.66	.98*	.44*	.79*				
5.	*SuppliersPatents*	Successful U.S patent applications by supplier	37.19	27.43	.97*	.30	.78*	0.92*			
6.	*MarketShareAssemblers*	Each automaker's market share in the U.S.	74.58	9.55	-.63*-	-.80*	-.84*	-.65*	-.58*		
7.	*USPatents*	Patenting activities of U.S. patenting firm	27.90	19.93	.92*	.17*	.72*	.86*	.95*	-.49*	
8	*ForeignPatents*	Successful U.S. patent applications by foreign firms	40.06	37.30	.97*	.80*	.80*	.99*	.93*	-.66*	.83*

[a] Significant at $p < 0.05$

[b] Logarithm of the expenditures at one year lag

TABLE 4
Regression Coefficients for Negative Binomial Models, Entire Patent Set

	Dependent Variable			
	FirmPatents		*TopFirmsPatents*	
Variables	Pooled Model		Firm Fixed Effects	
	Model 1	Model 2	Model 3	Model 4
LAG1 expenditure - 7073	0.061 ***		0.077 **	
	(0.014)		(0.022)	
LAG1 expenditure - 7477	0.0001		0.0001	
	(0.0005)		(0.001)	
LAG1 expenditure - 7881	-0.009 *		-0.005	
	(0.004)		(0.006)	
LAG1 expenditure - 8285	-0.001		0.004	
	(0.004)		(0.005)	
LAG1 expenditure - 8689	-0.035		-0.047	
	(0.030)		(0.049)	
LAG1 expenditure - 9093	0.003 ***		0.004 ***	
	(0.001)		(0.001)	
LAG1 expenditure - 9498	-0.0002		0.001	
	(0.002)		(0.002)	
MAP3 expenditures - 7073		0.061 *		0.079 *
		(0.025)		(0.034)
MAP3 expenditures - 7477		0.0003		0.0002
		(0.001)		(0.001)
MAP3 expenditures - 7881		-0.022 +		-0.010
		(0.012)		(0.017)
MAP3 expenditures - 8285		-0.005 +		-0.0001
		(0.003)		(0.004)
MAP3 expenditures - 8689		-0.002		0.005
		(0.017)		(0.026)
MAP3 expenditures - 9093		0.002 *		0.003 *
		(0.001)		(0.001)
MAP3 expenditures - 9498		-0.006		-0.004
		(0.004)		(0.005)
TotalAutoPatents	0.0002	0.002 +	-0.0005	0.001
	(0.001)	(0.001)	(0.001)	(0.001)
Constant	2.445 ***	1.678 **	-1.236 +	-1.849 *
	(0.424)	(0.592)	(0.652)	(0.828)
	Aggregated year dummies			
Period 74 - 77	1.540 ***	1.309 **	1.767 **	1.487 *
	(0.349)	(0.434)	(0.608)	(0.653)
Period 78 - 81	4.928 **	10.568 +	3.591	5.660
	(1.824)	(5.565)	(2.652)	(7.782)
Period 82 - 85	1.210	3.142 +	-1.569	0.910
	(2.344)	(1.609)	(3.153)	(2.413)
Period 86 - 89	27.188	1.467	36.523	-2.599
	(22.247)	(12.331)	(36.231)	(18.871)
Period 90 - 93	-	-	-	-
Period 94 - 98	2.560 +	5.859 *	2.643	5.659 *
	(1.536)	(2.324)	(1.724)	(2.713)
Log Likelihood	-108.547	-109.636	-737.006	-738.572
N	2098	2098	1287	1287

Standard errors are in parentheses
Some of year dummies dropped automatically due to multicollinearity
+p < 0.1; *p < 0.05; **p <0.01; ***p < 0.001
note: LAG1 - one year lag; MAP3- moving average of the prior three years

TABLE 5
Regression Coefficients for Negative Binomial Models, Assemblers' Patent Set

	Dependent Variable					
	AssemblersPatents		*TopAssemblersPatents*			
Variables	Pooled Model		Firm Fixed Effects			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
LAG1 expenditure - 7073	0.078 **		0.074 *		0.072 *	
	(0.023)		(0.031)		(0.029)	
LAG1 expenditure - 7477	0.001		0.001		0.0001	
	(0.001)		(0.001)		(0.001)	
LAG1 expenditure - 7881	-0.014 *		-0.009		-0.010	
	(0.006)		(0.007)		(0.007)	
LAG1 expenditure - 8285	0.0003		0.0001		0.001	
	(0.005)		(0.006)		(0.006)	
LAG1 expenditure - 8689	0.011		0.008		0.022	
	(0.043)		(0.060)		(0.058)	
LAG1 expenditure - 9093	0.004 ***		0.004 **		0.004 **	
	(0.001)		(0.001)		(0.001)	
LAG1 expenditure - 9498	0.0004		-0.0004		-0.001	
	(0.003)		(0.003)		(0.003)	
MAP3 expenditures - 7073		0.071 +		0.075		0.071 +
		(0.036)		(0.047)		(0.044)
MAP3 expenditures - 7477		0.001		0.001		-0.0001
		(0.001)		(0.001)		(0.002)
MAP3 expenditures - 7881		-0.036 +		-0.022		-0.025
		(0.019)		(0.022)		(0.022)
MAP3 expenditures - 8285		-0.007 +		-0.005		-0.005
		(0.004)		(0.005)		(0.005)
MAP3 expenditures - 8689		-0.024		-0.007		-0.010
		(0.023)		(0.032)		(0.031)
MAP3 expenditures - 9093		0.003 *		0.003 +		0.003 +
		(0.001)		(0.002)		(0.001)
MAP3 expenditures - 9498		-0.007		-0.005		-0.006
		(0.005)		(0.006)		(0.006)
TotalAutoPatents	0.0001	0.002	-0.0001	-0.005	0.00001	0.001
	(0.001)	(0.001)	(0.001)	(0.006)	(0.001)	(0.001)
MarketShareAssemblers					0.036 *	0.036 *
					(0.015)	(0.015)
Constant	0.791	-0.119	-1.152	-1.719	-1.564 +	-2.172 *
	(0.661)	(0.89)	(0.890)	(1.097)	(0.854)	(1.072)
	Aggregated year dummies					
Period 74 - 77	2.364 ***	1.946 **	2.156 **	0.001	2.000 **	1.759 *
	(0.594)	(0.664)	(0.825)	(0.001)	(0.766)	(0.821)
Period 78 - 81	8.172 **	17.43 *	5.811 +	-0.022	6.042 +	12.346
	(2.842)	(8.545)	(3.355)	(0.022)	(3.322)	(9.813)
Period 82 - 85	1.012	4.749 *	1.187	-0.005	0.452	3.532
	(3.36)	(2.278)	(4.392)	(0.005)	(4.402)	(3.084)
Period 86 - 89	-6.59	18.18	-4.401	-0.007	-14.77	8.155
	(31.81)	(16.73)	(44.43)	(0.032)	(43.28)	(22.397)
Period 90 - 93	-	-	-	-	-	-
Period 94 - 98	3.106	7.158 *	3.701 +	0.003 +	3.6 +	6.230 +
	(1.914)	(3.09)	(2.194)	(0.002)	(2.158)	(3.433)
Log Likelihood	-92.26	-92.55	-312.62	-319.35	-318.85	-319.35
N	954	954	799	799	799	799

Standard errors are in parentheses
Some of year dummies dropped automatically due to multicollinearity
+p < 0.1; *p < 0.05; **p <0.01; ***p < 0.001
note: LAG1 - one year lag; MAP3- moving average of the prior three years

TABLE 6
Regression Coefficients for Negative Binomial Models, Suppliers' Patent Set

	Dependent Variable			
	SuppliersPatents		*TopSuppliersPatents*	
Variables	Pooled Model		Firm Fixed Effects	
	Model 1	Model 2	Model 3	Model 4
LAG1 expenditure - 7073	0.056 ***		0.083 *	
	(0.013)		(0.032)	
LAG1 expenditure - 7477	-0.001		-0.0005	
	(0.001)		(0.001)	
LAG1 expenditure - 7881	-0.006		-0.002	
	(0.004)		(0.009)	
LAG1 expenditure - 8285	-0.001		0.008	
	(0.004)		(0.007)	
LAG1 expenditure - 8689	-0.069 *		-0.106	
	(0.033)		(0.078)	
LAG1 expenditure - 9093	0.002 ***		0.004 **	
	(0.001)		(0.001)	
LAG1 expenditure - 9498	-0.0002		0.002	
	(0.002)		(0.004)	
MAP3 expenditures - 7073		0.061 *		0.085 +
		(0.024)		(0.049)
MAP3 expenditures - 7477		-0.001		-0.0002
		(0.001)		(0.002)
MAP3 expenditures - 7881		-0.014		-0.002
		(0.014)		(0.027)
MAP3 expenditures - 8285		-0.003		0.004
		(0.003)		(0.006)
MAP3 expenditures - 8689		0.019		0.009
		(0.019)		(0.040)
MAP3 expenditures - 9093		0.002 +		0.003 +
		(0.001)		(0.002)
MAP3 expenditures - 9498		-0.004		-0.004
		(0.004)		(0.007)
TotalAutoPatents	-0.000001	0.001	-0.001	0.0005
	(0.0005)	(0.001)	(0.001)	(0.002)
Constant	2.397 ***	1.877 **	-1.360	-2.083 +
	(0.411)	(0.594)	(0.945)	(1.229)
	Aggregated year dummies			
Period 74 - 77	1.205 ***	1.057 *	1.522 +	1.165
	(0.346)	(0.428)	(0.883)	(0.953)
Period 78 - 81	3.006	6.479	2.086	1.642
	(2.053)	(6.239)	(4.109)	(12.054)
Period 82 - 85	0.959	1.753	-4.079	-1.825
	(2.606)	(1.801)	(4.491)	(3.699)
Period 86 - 89	52.188 *	-13.690	80.377	-5.669
	(24.204)	(14.045)	(58.147)	(28.897)
Period 90 - 93	-	-	-	-
Period 94 - 98	2.159	4.418 +	1.846	5.583
	(1.408)	(2.282)	(2.559)	(4.106)
Log Likelihood	-91.91	-94.09	-402.76	-403.88
N	1153	1153	488	488

Standard errors are in parentheses
Some of year dummies dropped automatically due to multicollinearity
+p < 0.1; *p < 0.05; **p <0.01; ***p < 0.001
note: LAG1 - one year lag; MAP3- moving average of the prior three years

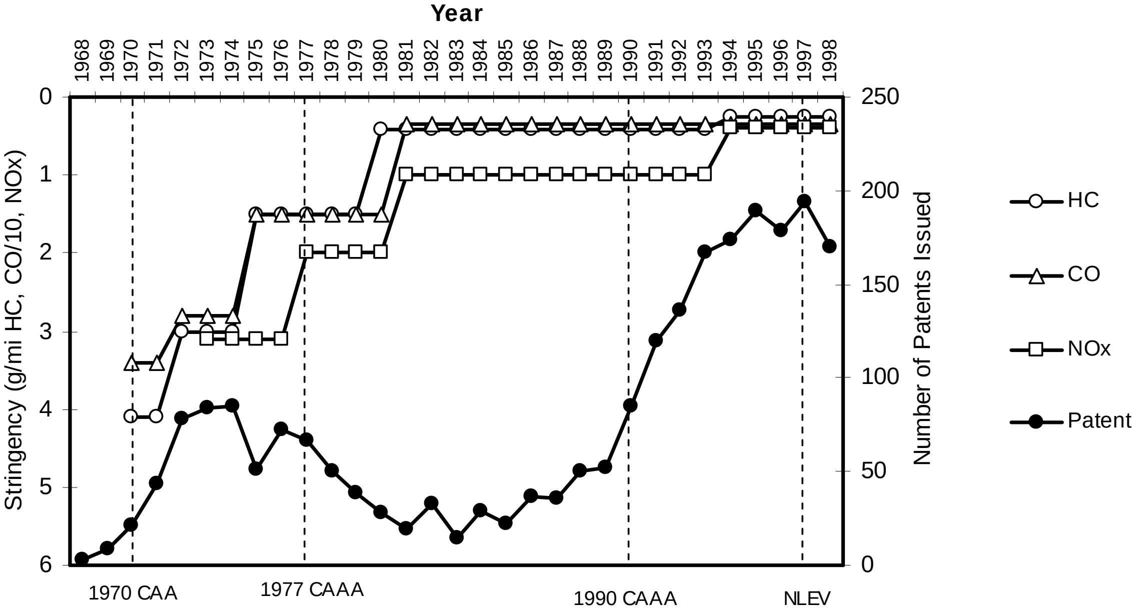
TABLE 7
Regression Coefficients for Negative Binomial Models, U.S. Firms' Patent Set

	Dependent Variable					
	USPatents			*TopUSFIRMSPatents*		
Variables	Pooled Model			Firm Fixed Effects		
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
LAG1 expenditure - 7073	0.040 **	0.025 +		0.049 *	0.049 +	
	(0.015)	(0.015)		(0.025)	(0.028)	
LAG1 expenditure - 7477	-0.001 *	-0.002 **		-0.001	-0.001	
	(0.001)	(0.001)		(0.001)	(0.001)	
LAG1 expenditure - 7881	-0.007	-0.005		-0.002	-0.002	
	(0.006)	(0.006)		(0.007)	(0.007)	
LAG1 expenditure - 8285	-0.003	-0.004		0.001	0.001	
	(0.005)	(0.005)		(0.007)	(0.007)	
LAG1 expenditure - 8689	0.003	0.018		0.0003	0.0002	
	(0.037)	(0.036)		(0.059)	(0.061)	
LAG1 expenditure - 9093	0.001 *	0.0002		0.002 +	0.002	
	(0.001)	(0.001)		(0.001)	(0.001)	
LAG1 expenditure - 9498	0.0002	-0.0003		-0.00004	-0.00004	
	(0.003)	(0.002)		(0.004)	(0.004)	
MAP3 expenditures - 7073			0.012			0.030
			(0.027)			(0.046)
MAP3 expenditures - 7477			-0.003 *			-0.002
			(0.001)			(0.002)
MAP3 expenditures - 7881			-0.013			0.002
			(0.017)			(0.021)
MAP3 expenditures - 8285			-0.003			-0.002
			(0.004)			(0.005)
MAP3 expenditures - 8689			-0.003			-0.018
			(0.020)			(0.032)
MAP3 expenditures - 9093			-0.001			0.0004
			(0.001)			(0.002)
MAP3 expenditures - 9498			-0.004			-0.008
			(0.004)			(0.007)
TotalAutoPatents	0.001	0.001	0.002 +	0.00006	0.00005	0.002
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
ForeignPatents		0.008 *	0.008 *		-0.00006	0.001
		(0.004)	(0.004)		(0.007)	(0.006)
Constant	2.222 ***	2.158 ***	1.831 **	-0.297	-0.296	-1.141
	(0.471)	(0.430)	(0.629)	(0.800)	(0.803)	(1.103)
			Aggregated year dummies			
Period 74 - 77	0.910 *	0.531	0.214	0.888	0.891	0.419
	(0.376)	(0.391)	(0.476)	(0.656)	(0.726)	(0.839)
Period 78 - 81	2.910	1.849	4.844	1.228	1.235	-0.833
	(2.655)	(2.634)	(7.766)	(3.248)	(3.370)	(9.859)
Period 82 - 85	1.299	1.716	0.242	-0.673	-0.677	0.769
	(3.321)	(3.200)	(2.113)	(4.377)	(4.398)	(3.098)
Period 86 - 89	-1.99	-13.69	1.06	0.41	0.50	12.69
	(27.69)	(26.80)	(14.68)	(44.30)	(45.61)	(23.37)
Period 90 - 93	-	-	-	-	-	-
Period 94 - 98	0.782	-0.103	2.156	1.611	1.617	5.912
	(1.845)	(1.692)	(2.530)	(2.905)	(2.989)	(4.358)
Log Likelihood	-88.56	-86.49	-87.71	-333.73	-333.73	-333.77
N	865	865	865	567	567	567

Standard errors are in parentheses
Some of year dummies dropped automatically due to multicollinearity
+p < 0.1; *p < 0.05; **p <0.01; ***p < 0.001
note: LAG1 - one year lag; MAP3- moving average of the prior three years

FIGURE 1

Regulation Stringency Levels and Patenting Activities in Automotive Emission Control Technologies, 1968 to 1998



Source: (Lee et al., 2004)