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Innovation and Technology Policy:
Lessons from Emission Control and Safety Technologies
in the U.S. Automobile Industry

By

Jaegul Lee
International Motor Vehicle Program
Massachusetts Institute of Technology
Cambridge, MA 02139
and
Business Department
School of Business Administration
Wayne State University
Detroit, MI 48202

David A. Hounshell
Department of Social and Decision Science
Carnegie Mellon University
Pittsburgh, PA 15213

Francisco M. Veloso
International Motor Vehicle Program
Massachusetts Institute of Technology
Cambridge, MA 02139
and
Department of Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213

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INTRODUCTION

In their sweeping and often-critical essay, "At the Intersection of Histories: Technology and the Environment," Jeffrey K. Stine and Joel A. Tarr explore "those gray areas" where the history of technology and environmental history overlap (Stine and Tarr, 1998). One of those gray areas, they argue, centers on the automobile, a technology that has received considerable attention from both historians of technology and environmental historians. As they note, although historians of technology have focused for decades on automotive design and manufacture, on the planning and construction of highways, and on the larger interactions of the automobile, society, and culture, they have paid almost no attention to the automobile as an environmental problem and have made no efforts to develop a history of automobile emission control technologies. A similar charge could be leveled against historians of technology when it comes to the topic of the history of automotive safety. Although they have been slowly developing an outstanding literature on safety issues surrounding other technologies (Burke, 1966; Sinclair, 1974; Sinclair, 1980; Tebeau and Tarr, 1996; Aldrich, 1997; Tarr and Tebeau, 1997; Usselman, 2000),[1] historians of technology have not selected the automobile as the central focus of their research in spite of safety concerns having always attended the development, adoption, and diffusion of the automobile. At its most basic level, this research aims to rectify these shortcomings in the history of technology by providing scholarly research in the history of technology that focuses on the automobile, emission control, and safety.

This research aims for much more, however. We seek to study the phenomena of innovation and technological development under what experts in government regulation have

[1] Some of the earliest and best literature in the history of technology focused on the steamboat, steam boilers, and the problems of railroad safety (Burke,1966; Sinclair1974; Sinclair,1980;Aldrich, 1977 and Usselman,2000). Other work has focused on the home as a site of safety problems (Tebeau and Tarr, 1996 and Tarr and Tebeau, 1997).

termed "technology-forcing" regulations (government-imposed regulations that force industries and/or firms to develop new technologies in order to meet the goals, objectives, or standards imposed by those regulations). Thus, our research not only endeavors to contribute to the history of technology (and to studies of science and technology more generally), but it also seeks to address areas of scholarship that focus on the economics of technical change, on the management of technology, and on business, government, and technology policy (especially regulatory policy). We approach this by contrasting two intimately related case studies: 1. development of technologies for controlling (i.e., reducing or eliminating) automobile pollution under technology-forcing regulation, and 2. development of technologies to make automobiles safer under technology-forcing regulation.

Beginning in the 1960s, U.S. automobile manufacturers increasingly faced two sets of demands to change the products they sold. One set of demands centered on making cars safer and resulted in the passage of the Highway Safety Act of 1966, the National Traffic and Motor Vehicle Safety Act of 1966, and the Highway Safety Act of 1970. This last act created the National Highway Traffic Safety Administration (as successor to the existing National Highway Safety Bureau established in 1967), which quickly mandated that automobile manufacturers provide "passive" protection technologies for front-seat occupants of new cars by July 1, 1973 and for all passengers by July 1, 1974.[2] The second set of demands on automakers centered on lowering the harmful emissions from cars and contributed (in part) to the passage of the 1965 Clean Air Act Amendments, the Air Quality Act of 1967, the National

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[2] We focus on the Occupant Crash Protection Standard under the Federal Motor Vehicle Safety and Standard and Regulations (FMVSS 208). FMVSS 208 specifies safety regulations for motor vehicles in terms of minimum safety performance requirements or items of motor vehicle equipment and encompass regulations for crash avoidance, crashworthiness, and post crash standards (http://www.nhtsa.dot.gov/cars/rules/import/FMVSS/). Unlike most other standards that specify standards in terms of equipment used, FMVSS 208 represents a first step toward general performance-based standards for motor vehicle safety regulations; the standard was framed "in terms of the effects produced on an anthropomorphic dummy in frontal barrier crashes at 30 miles per hour" (Mashaw and Harsft 1990).

Environmental Policy Act of 1969, and, most importantly, the Clear Air Act [Amendments] of 1970. Implementation and enforcement of the 1970 Clear Air Act—including its provisions for 90% reduction in automobile tailpipe emissions of hydrocarbons (HC) and carbon monoxide (CO) by 1975 and nitrogen oxide (NOx) by 1976--fell to a new agency, also created in 1970, the Environmental Protection Agency.

These events constitute what is as close to an ideal "*natural experiment*" for the historian and analyst of technological change as one could ever want: one now-regulated industry (automobile manufacturers), two sets of federal laws "with teeth" (the Highway Safety Act of 1970 and the Clear Air Act of 1970), and two new federal agencies (the National Highway Traffic Safety Administration and the Environmental Protection Agency) to enforce those laws and to ensure that by the early-to-mid-1970s the industry's cars would be both safer and less polluting. Although automobile safety and automotive emission-control technologies share, in one sense, the same political and regulatory milestone of 1970, although the same automobile makers were involved, and although the federal government was the principal regulator, the developmental paths in emission control and safety quickly diverged. Technological outcomes differed dramatically in spite of the automobile industry's fierce opposition to both sets of regulation. Although neither as smoothly nor as quickly as originally envisaged by the Clear Air Act of 1970, the American automobile industry began producing cars with technologies embedded in them that controlled targeted pollutants and that met increasingly stringent standards for automobile emissions. In the case of safety, the American automobile industry and the regulators of safety moved in fits and starts, changed courses, and, experts have argue, failed to meet the regulatory goals envisaged by lawmakers in the 1960s. Why this difference in outcomes? [3]

[3] We know of only a few works that even raise this question, and certainly those works do not seek to answer it based on systematic empirical research focusing on the technologies and technological pathways that have been central to these two cases and on the respective (and overlapping) networks of actors who comprised the *dramatis*

Prior research on explaining the success and failure of technology-forcing regulations attributed differential regulatory outcomes to differences in political and regulatory processes involved in the implementation, monitoring, and enforcement of these regulations (Gerard and Lave 2002). They argue that the EPA had greater credibility than the NHTSA in enforcing standards: the EPA had to rely on an Act of Congress to grant delays to target dates, while NHTSA had the leverage to delay standards. Consequently, their study suggests that it was more difficult for automakers to fight against the EPA than the NHTSA, and eventually led to an unfavorable impact on implementation of safety regulations.

Gerard and Lave (2002)'s analysis in explaining the differential regulatory outcome is based on their underlying judgment that the major automakers were able to develop suitable technologies within the time period given by the technology-forcing mandates.[4] However, we believe that mere introduction of system does not fully capture technological complexity, especially when the development technological system requires collaborative efforts between the component suppliers and automakers. For more accurate comparison of the two technological solutions, technology should be examined in greater details and should not just be treated as a "black-box."

Our methodological approach in this research is first to tackle this question by empirically examine the statistical relationships between innovative output (patent counts) and

personae of these two cases. Most studies have sought to argue the case of regulatory failure—either from a politically conservative perspective or from a politically liberal perspective. One work that seeks to answer this question from a still-different perspective is that of our CMU colleagues David Gerard and Lester Lave (both of whom are formally trained in economics) (Gerard and Lave, 2002). Their analysis of the differences in outcomes of these automobile-related technology-forcing regulations identifies differences in the implementation, monitoring, and enforcement of these regulations as the major factor, but it devotes no attention to the actual processes by which technological innovation occurred, the interaction among automakers and suppliers, and the R&D and capability-building activities carried out or supported by both the auto industry and the regulatory agencies themselves.

[4] Auto industry successfully introduced catalytic converters and airbag systems by 1975 and 1973 respectively.

lagged regulatory stringency. Statistical tests would help us determine whether the onset of technology-forcing regulations were effective in inducing innovation in automobile emission control and safety technologies. More importantly, we would be able to compare statistical findings from two cases and analyze auto industry's differential reactions to technology-forcing regulations for the development of emission control and safety technology.[1] Our previous research with automobile emission control suggests that the technology-forcing regulation was effective in driving innovation in automobile emission control (Lee, 2005; Lee et al., 2004). Using successfully applied patents as a measure of innovation both in automobile emission control and safety technologies from 1970 to 1998, the focus of this article is to expand upon our previous study in automobile emission control; and to compare and contrasts statistical results from two cases of technological development under the technology-forcing regulations.

This article is organized as follows: the next section describes theoretical background for the technology-forcing regulations and examples of recent research that examined the effectiveness of technology-forcing regulations on innovation. The following section discusses the historical context for automobile emission control and safety regulation. The paper then discusses the methods used to develop patent dataset and detailed descriptions of analyses used. The final section discusses the findings of statistical analyses and concludes with a discussion of principal findings regarding the influence of the technology-forcing regulations on innovation and firms' differential reactions to automobile emission control and safety regulations.

TECHNOLOGY-FORCING REGUALTION IN THEORY

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. 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.[5] Technology-based standards mandate that particular technological avenues or approaches be taken to meet the objectives. Technology-based standards can be 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, if regulators rely only on available, "off-the-shelf" technologies. Even under "best-available-technology" standards, which in theory call for firms to upgrade regularly to improved technologies, firms have little incentive to innovate and move the technology forward 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 and Stavins, 2003).[6]

Technology-forcing regulations can be implemented using either performance-based or technology-based standards. Under technology-forcing regulations, firms can be required to meet performance levels that are not considered to be feasible using current technologies, or they can be required to adopt specific technologies or technological pathways that have not been fully developed but which experts believe will, when perfected, achieve the regulators'

[5] As Robert Leone (Leone, 1999) points out, however, "Analysts are also aware that sometimes the practical consequences of setting a performance standard is to set a *de fact* technology standard because the performance requirements are based on a prototype technology. . . ." For more general literature on the theory of technology-forcing regulations, (Crandall and Lave, 1981; Breyer, 1982; Leone, 1986; Porter and van der Linde, 1995; Crandall et al., 1996)

[6] As Jaffe, Newell, and Stavins (2003) note, however, firms might receive public recognition for their efforts. (This article provides a nearly-state-of-the-art review of how economists conceptualize regulation and the incentives to innovate.)

goals. Thus, firms are forced to improve those particular technologies or pursue R&D in those mandated technological pathways to the point of satisfying regulatory standards or objectives (Jaffe, Newell and Stavins, 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).

Although there is considerable debate among economists about the relative efficiencies of market-based instruments versus command-and-control regulations (some of it ideologically driven), technology-forcing regulations are generally known or acknowledged to be successful in driving technological innovation.[7] Development of substitutes for chlorofluorocarbons (CFCs) is one of the most often-cited success stories of technological innovation in response to technology-forcing regulations. Banning the use of halogenated chlorofluorocarbons (CFCs) from aerosol applications by the Consumer Product Safety Commission and the Environmental Protection Agency under the Toxic Substances Control Act and the Montreal Protocol resulted in two innovations: the development of non-fluorocarbon propellants and new aerosol pumping systems that are cheaper than the ones they replaced (Ashford, Ayers and Stone,, 1985; McFarland, 1992; Parson, 2003). Also, as the work done by Taylor (2003), the development of increasingly effective, efficient, and less-costly flue gas desulfurization systems to remove SO_2 emissions from coal-fired electric power plants provides another example where technology-forcing regulations—the Clear Air Act Amendments of 1970 and the1971 New Source Performance Standards--stimulated innovation (Rubin et al., 2002; Taylor, Rubin and Hounshell, 2003; Rubin et al., 2004b). Finally, research by Jaegul Lee has shown similarly how the Clear Air Act Amendments of 1970 led the automobile industry (the car makers and their

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[7] For example, compare the findings of Jaffe, Newell and Stavins (2002) with René Kemp (Kemp, 1997). See also Porter and van der Linde (1995)

suppliers) to increase greatly their innovative activity in emission control systems (Lee et al., 2003; Lee, 2004).

In spite of these successes, the cost and availability of technology remain as primary sources of uncertainty in adopting technology-forcing regulations (Miller, 1995; Kemp, 1997). Regulators must have sufficient knowledge of the technologies or technological pathways that are to be “forced”--and also be able to assess accurately the innovative capacity of the target industry—in order to set the stringencies of performance standards such that they will indeed stimulate innovation and the development of new technologies, while reducing risks associated with regulatory uncertainties. Risks involved with regulatory uncertainties include forcing the development of technologies that become unnecessarily costly or fail to meet regulatory objectives.

TECHNOLOGY-FORCING REGULATIONS IN THE U.S, AUTOMOBILE INDUSTRY

Regulatory Context

Automobile Emission Control: The Clean Air Act (CAA) in 1970 and the Motor Vehicle Safety Act in 1966 are two regulations that adopted the technology-forcing approach in achieving regulatory goals. Realizing the need to establish a specific federal governmental agency with 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 and Omenn 1981). The newly created Environmental Protection Agency (EPA) specified 90% reductions in the 1970 levels of HC and CO emissions by 1975. It also required 90% reductions of 1971 NO_x levels by 1976 (White 1982). These standards can be translated as 0.41, 3.4 and 0.4 grams per mile for HC, CO and NO_x, respectively. However, automobile manufacturers mounted serious opposition, and the 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.

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 standards. 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).

Automobile Safety: The 1966 Motor Vehicle Safety Act (MVSA) and subsequent motor safety acts provide another example where regulation adopted a technology-forcing approach. Seat belts and shoulder harnesses were available on only 77-80 percent of motor vehicles by 1970 and only 25-30 percent of motorists were known to wear seat belts (Mashaw and Harfst 1990). To address this automobile safety concern, John Volpe, Secretary of Transportation, approved an advance notice of a proposed Rule 208 from NHSB in 1969, requiring that safety criteria stated in Rule 208, covering occupant crash protection, be met by a "passive restraint" system instead of an active system such as seat belts employed by drivers and passengers themselves (Graham 1989). More specifically, the standard mandated that the anticipated passive restratin system--airbags that inflate upon crash--would not inflict certain "injuries" on a 5'9" dummy in a frontal barrier crash at any speed up to and including 30 mph and frontal angles up to 30 degrees (NHTSA 2001; Safety_Forum 2004). NHTSA issued its final ruling in 1970 that passive protection systems be implemented by July 1, 1973 for front seat occupants and July 1, 1974 for all seating positions. John Volpe's public statements in 1969 made clear to the industry that inflatable restraints were meant to be an airbag system (Graham 1989). See **Table I**, "Key Legislative Histories for Automobile Emission and Safety Control," for a quick view of the parallels and departures in the regulatory histories of these two "forced" technologies.

[Insert Table 1 here]

Firms' Differential Reactions to Technology-Forcing Regulations

What is interesting about the 1970 CAA and the 1966 MVSA regulations is that regulatory outcomes were different. The history of the development of emission control technologies for automobiles reveals that the 1970 CAA led to the introduction and implementation of emission control technologies for automobiles in the 1970s (Mondt 2000; NESCAUM 2000). Resistance to the 1970 CAA from automobile manufacturers was severe. Lee Iacocca, Executive Vice President of Ford, made a statement to the press in 1970 in which he claimed that the amendments to the Clean Air Act could do “irreparable damage to the American economy [which] exemplifies automakers’ resistance to the regulation” (Iacocca 1970). Nevertheless, the 90% pollutant reduction requirement in automobile emissions eventually led the auto industry to come up with catalytic converters designed for automobiles (Mondt 2000; Lee, et al., 2003). Figure 1 shows federal automotive emission standards for the period 1970 to 2004 and the time at which emission control technologies for automobiles were introduced. The phasing in of more stringent emission control standards drove innovation in emission control technologies: oxidation catalysts in 1975; three-way catalysts in 1980, and thermal management and onboard diagnostic systems in 1994. Further, advanced catalyst technologies, such as high-density and hexagonal cell-structured catalyst support, and advanced engine control systems, such as electronic exhaust gas recirculation and fuel injectors with improved fuel atomization, are being developed to satisfy the stringencies of the Tier II standards (Bertelsen 2001).

[Insert Figure 1 here]

Unlike technology-forcing on emission control, technology-forcing on passive restraint systems was not as successful (Graham 1989; Gerard and Lave 2002). After NHTSA mandated its rule on passive restraints in 1970, GM introduced the airbag to its Chevrolets in the 1973 model year for field testing. One thousand Chevrolets had airbags installed (Graham 1989; Gerard and Lave 2002). GM further ordered 100,000 of Eaton Corporation’s airbag sensor systems and started to offer airbags as an option for some of its 1974 models (Graham 1989). However, GM withdrew from its airbag program by 1976 and stopped offering airbags in 1977. Ford postponed adopting airbag systems for their models in favor of interlock technology, which was also approved by NHTSA as an alternative to a passive-restraint safety device in October 1971. The interlock system is the technology that is designed to prevent automobiles from starting when drivers or passengers do not buckle up. GM’s first introduction of airbags from 1974 to 1976 ended up selling only 10,000 units, in spite of GM's technical leadership in airbag systems. Considering that vehicles equipped with airbags were not required also to contain the unpopular starter-interlock system, the sale of only 10,000 units is remarkably low. GM joined the rest of the automakers and turned against the passive-restraint regulation after its failure in promoting airbags.

Airbags reappeared in automobiles about 15 years after their first introduction in 1973. Chrysler first adopted airbags as standard equipment in all its domestic cars in 1988. Other manufacturers such as Ford also started installing airbags in their models in 1989. According to Graham (1989), the automakers' decision to offer airbags in the late 1980s was driven largely by market forces rather than by technology-forcing regulation (Graham 1989). Automakers started to pay greater attention to safety as related to customer satisfaction and sensed that the market was increasingly willing to pay an additional price for enhanced safety.

METHODS

We carry out empirical studies of technology-forcing regulations and technological development by performing systematic analyses of innovative activity over time (as measured by patents) and correlate such activity with government actions, including regulation. The methods that we have employed in patent counting, in which we use not only class-based searches but also key-word searching and subsequent cleaning of irrelevant patents, have allowed us to analyze how innovation in what we call "environmental and safety technologies" proceeds *under* technology-forcing regulation. We further carry out a rigorous comparative analysis of the patterns of innovation in both automobile emission control and safety technologies as they relate to the *anticipation, establishment, and enforcement* of technology-forcing regulations and later modifications (sometimes increased stringencies, sometimes relaxation of previously promulgated stringencies).

Data

Patent Database: We use successfully-applied-for patent counts as a measure of innovation activities. Patent counts are known as imperfect measures of innovative outputs (Griliches 1990; Archibugi and Pianta 1996; Lanjouw, Pakes and Putnam, 1998). Not all inventions and/or innovation are patented, and quality of individual patents varies quite widely (Lanjouw, Pakes and Putnam, 1998; Popp 2005). Popp (2005, pg. 214) argued that results of patent research should, thus, be interpreted "as the effect of an 'average' patent, rather than any specific invention." Nevertheless, patent statistics have been extensively used by academics studying technological changes (e.g. Jaffe and Palmer 1997; Trajtenberg 2001; e.g. Popp 2002; Popp 2006). One of the biggest advantages of using patent data is that it offers an abundant quantity of data complete with organizational and technical details (Lanjouw, Pakes and Putnam, 1998). Also, patent data allows construction of a time-series database (Popp 2003).

We developed relevant patent sets using patent data from the U.S. Patent and Trademark Office (USPTO). We employed abstract-based keyword search methods in addition to using more conventional patent class-based searching methods. Our purpose in adopting 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; thus, any complex technological system that possesses multiple subsystems, such as automobile emissions control technologies, likely belong to multiple patent classifications. Consequently, relying only on patent classifications alone runs a 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 for the use of a catalyst for pollution control 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 similar reason, relevant patents of interests may also belong to other patent classes not captured by a researcher. Abstract-based keyword search allows researchers to double check their search findings under patent class-based search approach, and it enables them to identify potentially relevant patents not found under class-based search.

For automobile emission control technologies, we selected seven different keywords for an abstract-based keyword search: catalytic converter, emission, automobile, catalysts, pollution, exhausts, and engine. These keywords were then permuted 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 representing catalytic converter technology from prior patent studies on catalytic converter technology (Campbell and Levine 1984). The process for obtaining relevant patents using class-based searching was similar to that of abstract-based keyword search. We used patent application date rather than patent grant date to reflect more closely the timing of inventors' propensity to patent, thereby avoiding vagaries involved in patent-granting processes (Griliches 1990).

We identified a total of 2,108 successfully-applied-for automotive emissions control patents by firms for the period between 1968 and 1998. Major patent classes/subclasses representing automotive emissions control technologies found are listed in Table 2.

[Insert Table 2 here]

For automobile safety technologies, we used 15 different keywords for abstract search: airbag, seatbelt, seat, fuel, impact, signal, transmission, brake, steering, window, head restraints, bumper, glass, tire and theft.[8] We pursued similar steps to identify relevant patents in safety technologies: identified keywords were permuted to search the U.S patent database electronically, and searched patents were screened to generate a set of relevant patents. Total number of identified patents in automobile safety technologies is 6,357 for the period 1968 to 1998. Major patent classes/subclasses for safety technologies are listed in Table 3.

[Insert Table 3 here]

Results of our patent searches are shown in Figure 2 (note that the Y-axis contains separate scales for the two technologies). Patenting in safety technology is found to be significantly higher than that of emission control technologies, yet the overall pattern in patenting activities in both technologies share remarkable similarities. Patenting in both technologies increased during the 1970s and 1990s and declined noticeably in the 1980s.[9] In order to provide a detailed accounting of technological evolution at a subsystem level,[10] we disaggregated patenting activities in both emission control and safety technologies into four main sub-technology categories (Figure 3).

[Insert Figure 2 & 3 here]

Expenditure Estimates: We used cost estimates for automobile emission control and safety devices as the compliance cost data. For automobile emission control devices, cost data came from number of different sources that include the EPA (1990) and the California Air Resource Board (CARB 1996) instead of using the Pollution Abatement Costs and Expenditure

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8 Keywords used for search are selected based on the safety technologies covered under the Federal Motor Vehicle Safety Standards (FMVSS).

9 We suspect that innovation in the auto industry is, in general, sensitive to regulatory environments. Our subsequent statistical analysis shows that heightened regulatory pressures in the 1970s and 1990s, and the presence of anti-regulation sentiments during the Reagan administration in the 1980s relate significantly with the amount of innovative activities as measured by patenting.

10 Complex technological systems typically consist of hierarchically structured subsystems. See L. Rosenkopf and A. Nerkar (Rosenkopf and Nerkar 1999).

(PACE) surveys. PACE data is inadequate for our study as we focus on specific technologies. Moreover, PACE data possesses many shortcomings as a measure of regulatory stringencies and may fail to capture potential links between regulations and the performance of consumer products such as auto-emission standards (Jaffe and Palmer 1997).

EPA's own study (EPA 1990) provides aggregated cost estimates for emissions control systems from 1972-1993[11] that include: evaporative emissions canisters from Model Year (MY) 1972, high altitude emissions controls from MY 1984, catalytic converters beginning MY 1975, exhaust gas recirculation units for MY 1973-1974, and air pump units for MY 1970-1974 (EPA 1990; McConnell, Walls et al. 1995). Analytical procedures and assumptions used for calculations can be found in McConnell et al.'s Resources for the Future Discussion Paper (McConnell, Walls et al. 1995).[12]

Notable increases in device costs occurred in 1975 as industry introduced oxidation catalysts to satisfy intermediate emission standards. Moreover, there is a steep increase in cost estimates from 1980 until 1984. This increase in costs seems to capture associated costs of introducing more advanced three-way catalysts with electronic loop control. EPA's 1990 study (EPA 1990) reveals that it cost an additional $746 per vehicle to achieve 90% reductions of tailpipe emissions from *pre*-1970 emission levels. Further study by the EPA using the data from the US 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 and Sherwood 2002). The Tier I standards, which phased-in in 1994 due to the enactment of the Amendments of the Clean Air Act in 1990, caused an additional cost of approximately $97 (Anderson and

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[11] EPA's study report (EPA 1990) that the costs of device remain constant after 1984. This research assumes that the costs of devices remain constant until the phase-in of more stringent Tier 1 standards in 1994.

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

Sherwood 2002).

Cost data for automobile safety devices for passenger cars, 1968 – 2002, came from NHTSA's 2004 report (NHTSA 2004). As a part of NHTSA's on-going evaluations of the Federal Motor Vehicle Safety Standards (FMVSS) since 1975, it published a report on the life-saving benefits and costs for a substantial "core" group of safety technologies for passenger cars. The "core" group of safety technologies includes: 1) Dual master cylinders (FMVSS 105), 2) Energy-absorbing steering assemblies (FMVSS 203/204), 3) Safety belts (FMVSS 208), 4) Front airbags (FMVSS 208), 5) Side door beams (FMVSS 214), and 6) Roof crush strength (FMVSS 216).[13]

Our approach in this paper is first to examine potential statistical linkage between innovative activities and regulatory stringencies embedded in the series of technology-forcing regulations. We then attempt to infer any new insights from regression results regarding firms' innovative behavior under regulatory pressures. Finally, we assess the effectiveness of technology-forcing policy instruments in stimulating technological change.

Model

We use a negative binomial specification to analyze quantitatively the impact of regulation on innovation. The negative binomial model accounts for both the count nature of the patent data and repeated time series cross-sectional observations —panel data (Hausman, Hall et al. 1984). In this analysis, we control for likely errors involved with patents as innovative outputs by using firm-level patenting activities instead of aggregated industry-level

[13] The cost report excludes any safety technologies that were introduced on a voluntary basis, introduced well before NHTSA's regulatory process or that of other government agencies, and those that did not result in a cost increase. Refer to NHTSA (2004) for more detailed description of NHTSA's categorization of "core" and excluded technologies.

patenting activities and time dummies. A conditional mean specification for the negative binomial function is as follows:

$$E(FirmsPatents_t \mid ComplianceCosts_t, TotalAutoPatents_t, \mu_t)$$
$$= Exp\{\beta_0 + \beta_1 * \log(ComplianceCosts)_{t-\tau} + \beta_2 * TotalAutoPatents_t + \mu_t\}.$$

where *t* represents years, *FirmsPatents* is successful U.S. patent applications in year t by patenting firms for either auto emission control (PATENT_EMISSION) or auto safety (PATENT_SAFETY), and *ComplianceCosts* represents regulatory compliance costs measured by estimated total expenditures on emission control and safety devices. *TotalAutoPatents* is the total innovation activity in automotive technologies, and its inclusion in the equation ensures that results obtained for patenting activities in emissions control technologies (or safety technology) are not just a reflection of an overall trend in innovations in automotive technologies. We use 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 1968 to 1998. We also built in lag structure[18] for expenditures to the model. We expect firms to invest in R&D prior to the phase-in regulatory stringency as firms, especially in the auto industry, are known to have long product lead times (Clark and Fujimoto 1991).

In order to examine the impact of regulatory pressures on technological change more closely, we ran similar regressions as discussed above using patenting activities in major subsystems as the dependent variable: catalysts and electronic feedback control for automobile emission control technologies and airbag and seatbelts for automobile safety technologies. Subsystem level analysis permits examination of technological change at a finer level. For

[18] We use two lag structures – one- and two-year lags – for expenditures.

example, according to the history of the development of automobile emission control, the auto makers and specialty chemical firms focused on introducing emission-reducing catalysts in the early 1970s. Once they successfully introduced catalysts in 1975, their focus of innovation gradually shifted to electronics that enabled them to monitor and control air-to-fuel ratios required for the operation of more advanced three-way catalysts. We expect that by separately running regressions on patenting activities of each major subsystem, we can examine the impact of regulatory pressures on innovation more precisely.

We also design another model specification to test for whether stringencies implicit in “technology-forcing” regulations caused U.S. firms to become more innovative compared to foreign competing firms in the U.S. market. We use patenting activities of U.S. firms in our patent database as a dependent variable and adopt patenting activities of foreign firms as an additional control variable.

$$
\begin{aligned}
&E(USPatents_t \mid ComplianceCosts_t, TotalAutoPatents_t, MarketShareForeignFirms_t, ForeignPatents_t, \mu_t) \\
&= Exp\{\beta_0 + \beta_1 * \log(ComplianceCosts)_{t-\tau} + \beta_2 * TotalAutoPatents_t \\
&+ \beta_3 * MarketShareForeignFirms_t + \beta_4 * ForeignPatents_t + \mu_t\}
\end{aligned}
$$

where *USpatents* is the patenting activities of the U.S. firms in the patent database, and *ForeignPatents* is successful U.S. patent applications by foreign firms. Inclusion of the *ForeignPatents* variable is designed to control for the rate of foreign patenting in auto emission control. *MarketShareForeignFirms* is aggregated market share held by foreign assemblers in year t. We acknowledge that *MarketShareForeignFirms* could be a crude measure for competitive market pressures for U.S. firms since U.S. component suppliers may have collaborated with foreign automakers, such as Toyota and Honda. Yet, historical accounts of the development of automobile emission control systems in the U.S. reveal that U.S. automakers were engaged principally with major U.S. catalyst- and substrates-producing firms, such as Engelhard and Corning, rather than foreign suppliers (Doyle 2000).

RESULTS AND DISCUSSIONS

Table 4 provides descriptive statistics and inter-correlations among variables used in the analysis. We first begin our discussion by examining the significance of key explanatory variables. We also closely observe any systematic patterns in the time dummy coefficients that correspond to stringencies embedded in regulatory events (e.g. 1970 CAAA and/or 1990 CAAA) over time. We then separately examine and compare regression results of key subsystems' patent sets: catalysts and electronic feedback control for automobile emission control technologies, and airbag and seatbelt for automobile safety technologies. Finally, we analyze regression results for the patent set drawn from U.S. firms to determine whether federal technology-forcing regulatory regimes caused higher patenting rates for domestic U.S. firms after controlling for factors that include the rate of foreign patenting and market share held by foreign auto assemblers.

[Insert Table 4 here]

Induced Technological Change in Automobile Emissions Control, Overall Picture

Results of cross-sectional time series negative binomial regression models for auto safety and emission technologies, subsystem level technologies and U.S. firms' patent sets are shown in Table 5 to Table 8 respectively.[19]

[Insert Tables 5-8 here]

Coefficients reported in the tables show that the total automotive patenting variable is highly significant even after controlling for other variables and time dummies, suggesting that patenting in both the automobile emission control and safety technologies reflects overall

[19] We only report regression results with one year lagged cost of compliance variable. We found similar results with two year lagged cost of compliance variable. Unreported results are available from authors on request.

patenting in automotive technologies during the same periods. The foreign patenting variable is also found to be significant (Table 8), implying that foreign patenting could be used as an important proxy for measuring the degree of innovation and attractiveness of patent protection in the industry (Jaffe and Palmer 1997). The variable, *MarketShareForeignFirms*, which represents the market share held by foreign assemblers in the automobile safety patent set, is negative and significant (Table 8). This finding supports the idea that competitive market pressures by foreign firms account for automakers' innovation activities, suggesting that firms tend to reduce investments in R&D when faced with significant competitive market pressures by foreign firms. Yet, this variable is not significant for automobile emission patent set. Further research is needed to resolve this difference in findings.

The lagged compliance cost variable, *LEXPEN1_Safety* was found to be significant for the safety patent set. As discussed above, inclusion of a compliance cost variable is to estimate the potential impact of regulatory stringencies on innovation (Tables 5, 7 and 8). This finding thus implies that the regulatory pressures in the form of higher stringencies stimulated innovation in the case of automobile safety technologies. Empirical findings using subsystem level patenting data (e.g., airbag and seatbelt for safety technologies) also confirm the finding that the lagged compliance cost variable is significantly related to firm patenting in automobile safety technologies (Table 7). According to the subsystem level regression analysis for automobile safety technologies, the coefficient on the lagged compliance cost variable is significant for airbag technology but is not significant for seatbelt technology. These findings suggest that while the regulatory actions in the form of technology-forcing have significant impact on innovation activities involved in the development of automobile airbag technology, regulatory stringencies' impact on innovation in automobile seatbelt technology is minimal—findings that seemingly comport with common sense. The findings that the regulatory actions have detectable impact on the development of automobile safety technology—especially airbag technology--is somewhat contrary to the claims of previous research, which claimed that the introduction of airbags was driven mainly by market forces (Graham 1989; Mannering and Winston 1995). Yet, unlike prior studies relied on perceptual research methods such as interviews (Graham 1989) and surveys (Mannering and Winston 1995),[20] findings of this research is strongly supported by systematic empirical analyses using longitudinal patent dataset encompassing the key regulatory periods in automobile safety between the late 1960s and the early 2000s.

Interestingly, while the lagged regulatory compliance cost variable for safety technology is significant, the lagged regulatory compliance cost variable for emission control technology, *LEXPEN1_Emission*, is found to be insignificant throughout the different model specification (Tables 5, 6 and 8). However, we believe that it would be premature to conclude that the regulatory pressures were not effective in driving innovation in automobile emission control. In fact, the finding that the compliance variable cost is insignificant is not unexpected. Unlike the 1970s and 1990s, the automobile industry involved in the development of emission control systems was mostly free from regulatory pressures in the 1980s. Thus, in the case of automobile emission control, a plausible connection between the cost of compliances and innovation activities in the 1970s and 1990s may not be correctly reflected in the cost of the compliance regression coefficient, mainly because the model calculates the average impact of cost of compliance on innovation over the entire period of study—rather than in separate periods under different policy regimes.

This suggestion that the regulatory pressures on innovation in automobile emission control systems are not correctly captured by a single regulatory compliance cost variable (*LEXPEN1_Emission*) is supported by systematic trends observed in year dummy variables.

[20] Surveys directed to study consumers' willingness to pay for airbags and automakers' responsiveness to consumers' willingness to pay

We observe a systematic pattern in the year dummy coefficients that correspond to stringencies mandated under the Amendments to the Clean Air Act in the 1970s and 1990s; year dummy coefficients in the 1970s and the 1990s are positive and significant throughout the models (Table 5 and Table 6). Considering that a series of Amendments to the Clean Air Act mandated that automakers introduce cars with more advanced emissions control technologies in the 1970s and 1990s, it is not surprising to observe that year dummies in the 1970s and 1990s turn out to be positive and significant. Systematic patterns of year dummy coefficients are evidenced in Figure 4 where year dummy coefficients are plotted. One can clearly see that year dummies in the patent regression continuously increased after the enactment of key regulatory actions for both the automobile emission control and safety technologies, reflecting the non-trivial impact of technology-forcing regulatory actions in inducing firm innovation activities.

[Insert Figure 4 here]

Another piece of evidence that year dummies capture regulatory stringencies can be found in the observation that regression coefficients of year dummies increase until a few years (one to three years) prior to the mandated product phase-in schedule. Year dummies increase until either 1976 or 1977 and decrease over the rest of the decade in the 1970s reflecting the phase-in of 90% reduction requirements in the 1980 and 1981 for HC and CO, and NO_x respectively; similarly, in the 1990s, year dummies increase until either 1992 or 1993 and then decrease, reflecting the phase-in of the 1990 CAAA regulation. This finding accords with the widely shared view that firms have a higher propensity to innovate *in advance* of the product phase-in date. It is important to remember that stringency levels are associated with vehicle models that were to be sold in the market in that year. This is particularly relevant for the automobile industry, which typically has long product lead times (Clark and Fujimoto 1991).

Technology-Forcing Regulations and the Porter Hypothesis

Table 8 shows the result of regressions using the U.S. firm patent samples. For the emission control patent sample, we find that year dummies from 1970 to 1974 are positive and significant, but year dummies in the 1990s are rather weakly related to regulation – only the 1991 year dummy is significant. This finding seems to suggest that technology-forcing in auto emissions regulations caused U.S. firms to innovate comparatively more than foreign competitors, yet such "innovation offset" effects occur only to a limited extent prior to 1975. Only the 1970 CAAA regime seems to be related to "innovation offset" for U.S. firms.

The idea that innovation offsets tend to occur in the early phase of market creation was discussed by previous theoretical work in the environmental policy and management literature. Discussing a pollution-abatement equipment industry within the framework of strategic environmental policy, Feess and Muehlheusser (2002) suggest that the realization of *the Porter hypothesis* through gains from learning would be most likely in the early development of an environmentally-related industry. This view assumes the presence of learning-by-doing in the pollution abatement equipment industry. Greaker (2006) shows that stringent regulations have an higher upstream price effect for new pollution abatement equipment,[21] and its effect would likely be higher when a well-established market for equipment does not yet exist. Schmutzler (2001) claims that there is a link between the likelihood of organizational inefficiencies responsible for innovation offsets and market environments. He argues that managers would typically lack incentives to invest in long-term R&D in an inefficient market, and there would then be a negative relationship between the likelihood of innovation offsets and the effectiveness of the market. Although this research does not explicitly provide evidence for the existence of learning in the equipment industry or in the managers' incentive scheme involved

[21] A stringent environmental regulation tends to increase entry of firms into upstream pollution abatement service sector and, thus, causes the supply curve for pollution abatement devices to shift downward (Greaker 2006).

in the development of automobile emissions control systems, our empirical findings, along with prior theoretical work, provide a key starting point for understanding the complex inter-relationship between innovation offsets, timing and stringency of the regulations, and the overall market environment.

For our automobile safety patent sample, year dummies from 1965 to 1972 are significant and positive (Table 8), confirming the finding from the automobile emission patent sample that the innovation offsets tend to occur in the early phase of market creation. What is interesting about the automobile safety patent sample is that year dummies from 1986 to 1990 are also positive and significant (Table 8). According to the history of the development of the automobile safety technologies, the market for the automobile airbag system did not really emerge until the late 1980s despite the fact that the first installation of the airbag system for automobiles occurred in the early 1970s.[22] Thus, the finding that year dummy coefficients are also positive and significant from 1986 to 1990 reflects the establishment of an airbag market for automobiles in the late 1980s. This observation, however, in no way suggests that the establishment of a market of airbags in the late 1980s vitiates the effectiveness of early technology-forcing regulation in the invention and development of air bags and related systems.

CONCLUSIONS

In this paper, we presented quantitative empirical evidence that technology-forcing regulations imposed on the automobile industry stimulated innovation in pollution abatement and safety equipment. In our models, we find a statistically significant relationship between the

[22] General Motors and Ford first offered automobiles with airbags for fleet tests in 1973 and 1971 respectively, and General Motors started to manufacturer Cadillac, Oldsmobile and Buicks equipped with airbags for sale in 1974. Major auto assemblers such as GM and Ford dropped offering optional airbags in the late 1970s due to poor sales performances and controversies over the safety of the airbag systems for the out-of-position occupants. Airbags in automobiles reemerged in the 1988 when Chrysler started to install driver airbags as standard equipment for all its domestic cars (Graham 1989).

cost of compliance variable and the patenting activities for the innovation in automobile safety technologies. This finding provides important evidence that the technology-forcing regulatory actions have had a detectable impact on the innovation activities related to the development of automobile safety technologies. However, we find no significant relationship between the cost of compliance variable and the regulatory stringency in the case of automobile emission control technologies. Considering the fact that the period of *no* additional regulations (during the 1980s) occupies approximately 30% of the entire period of the study, the regression coefficient of the cost of compliance—which shows an averaged correlation between the stringency and patenting activity over the entire period of the study—would likely underestimate the impact of regulation in the adjacent decades of the 1970s and 1990s. Importantly, we find some evidence for a significant relationship between regulatory stringency and patenting activity from a systematic pattern observed in year dummies. In a model where we controlled for market pressures, overall patenting trends in automotive technologies, and capital expenditures for pollution abatement devices, the coefficients of year dummies—the inclusion of which is intended to capture any time-dependent R&D determinants—remain significant only during the periods that correspond to regulatory regimes in the 1970s and 1990s. We also observed similar systematic patterns in year dummies with our automobile safety patent sample as well.

Our study offers several insights regarding the relationship between performance-based regulatory standards and the industry's innovative responses. First, properly designed command-and-control (CAC) type regulations can provide incentives for R&D. Empirical findings that CAC regulations provide incentives for R&D was also reported by Taylor, Rubin and Hounshell (2005) and Popp (2003) for the case of SO_2 control. Popp (2003) shows that technology-based CAC regulations used for SO_2 emissions control indeed led to R&D efforts toward lowering the cost of complying with the regulations. We do not provide here any additional set of evidence that CAC regulations provide greater R&D incentives than market-based approaches, but we would stress that properly designed CAC regulation can induce sufficient technological change to meet regulatory environmental goals.

Second, we suspect that CAC regulations, specifically performance-based CAC regulations, can be a useful regulatory tool to induce *radical* technological change—that is new technology that is well beyond the far more common incremental innovation. Prior theoretical studies that compared the effectiveness of regulatory tools and R&D incentives have favored market-based approaches (e.g. Jung, Krutilla and Boyd, 1996; Requate and Unold, 2003). However, Jones and Klassen (2002) claim that radical technologies tend to be difficult to introduce even if clear incentives for their adoption exist since radical innovations tend to be more competence-destroying for incumbent firms. Incumbent firms' reluctance to adopt radical technologies is clearly evident in the history of automobile emissions control in the U.S. Automakers at first were unwilling to adopt add-in type catalytic converters, and instead pursued modifying existing engine components in their attempts to reduce tailpipe emissions (Mondt 2000). Yet, the stringency of emission control, especially the requirement that NOx be controlled to less than 1.0 gram per mile, forced automakers to surrender their incremental innovation approach in the early 1970s of reducing emission control using engine modifications. A similar case of the emergence of radical technology in response to regulatory forcing can be found with California's initiative in stimulating the development of cleaner cars that encompass categories of vehicles from low-emission vehicles (LEVs) to zero-emission vehicles (ZEVs) (Schot, Hoogma and Elzen, 1994). To automakers, realization of ZEV represents another case of competence-destroying radical technological change since the introduction of the first catalytic converters in 1975: ZEV technologies require a fundamentally different drive-train mechanism from conventional internal combustion engine vehicles. Nevertheless, California's regulation that mandated a phase-in of ZEV not only induced development of ZEVs[23], but it also catalyzed the development of super ultra-low emission vehicles (SULEVs), such as battery-equipped hybrid vehicles (Majumdar 2005).

Third, observations that stringent, technology-forcing regulation drove technological innovation clearly supports the view that regulation stringency is a key determinant for the degree of induced technological change (Ashford, Ayers and Stone, 1993). More interestingly, we acknowledge that adoption of radically new technologies under high regulatory stringency may imply changes in the direction of future technological innovation. Further, our finding that suppliers' innovative responses to regulatory stringency in the 1970s differed from their responses in the 1990s suggests that understanding characteristics of technological evolution and the direction of technological change may have important implications for the success of regulation for inducing technological change. Yet, our understanding is limited on how radical technologies within regulatory environments compete and get selected from among competing technological options. Thus, future studies that examine potential connections between regulatory stringency and the selection mechanism among a variety of competing technological options may further enhance our understanding regarding the impact of regulatory stringencies on innovation.

Our finding that U.S. firms' innovative activities were significant under the U.S. auto-emissions regulations (during the 1970 CAAA regime) and safety standards (during the 1966 MVSA and the 1984 Reinstatement of Passive Restraint Rule) -- even after we controlled for foreign patents, provides important evidence for *the Porter hypothesis*. In other words, U.S. auto-emissions and safety standards caused U.S. firms to become comparatively more innovative than foreign competitors. However, our findings are limited in offering any

[23] Yet, implementation of ZEVs in California is limited due to the status of technology development in the U.S automobile industry. California's Air Resource Board and the auto industry are going through a series of revisions to ZEV and partial ZEV mandates to accommodate the realities of technological development in the industry (Majumdar 2005).

additional evidence to infer further whether firms' increased innovative activities in response to regulatory pressures came at the expense of their other R&D programs. Based on the fact that auto-emissions standards are performance-based, 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 and Palmer 1997, pg. 601)." According to Rugman and Verbeke (1998), the Porter hypothesis only applies to countries that possess a large domestic market (such as the U.S.) and whose governments have a significant influence on international regulation trends. Thus, following Rugman and Verbeke's argument, the U.S. auto industry—which has the most stringent auto-emissions and safety standards—is likely to benefit (or have benefited) from the regulations studied here, assuming that differences in stringencies of auto emissions and safety standards of U.S. and other countries diminish over time (Homeister 2001). In the case of U.S. auto-emissions regulations, firms in the specialty chemicals and electronics industries entered the market for auto emissions control technologies such as catalysts, substrates, and electronics sensors. Literature in the environmental strategy suggests that suppliers' incentives in entering the environmentally regulated industry could be understood from the point of view of the resource-based theory of the firm (Hart 1995). Firms that possess proactive strategies toward environmental issues tend to invest early in new pollution prevention technologies to gain competitive advantages over their rivals as proactive firms because first (or early) movers may benefit from proprietary cost-reducing or sales-enhancing technologies (Shrivastava 1995; Nehrt 1996; Russo and Fouts 1997; Aragon-Correa 1998; Klassen and Whybark 1999). Following the stream of research in environmental strategy, an extension of this paper that examines in detail how suppliers' existing capabilities, their decisions to diversify (or to enter de novo) into an upstream equipment industry sector relevant to auto emissions and safety and their long-term performance would be of great interest. One key limitation of this paper is that we relied on aggregated industry-level patenting activities; thus, factors that are associated with firm level unobservable heterogeneities are not properly accounted for. Firms may have different strategies in terms of technological investments, and firms' patent strategies may even differ depending on their R&D intensities (Arundel and Kabla 1998). Firms from different countries may also have different propensities to patent. Inclusion of firm fixed effect models eliminates biases from those firm heterogeneities. Future research that explores how key assemblers and suppliers involved in automobile safety and emission-control development collectively reacted to regulatory pressures; the complex inter-relationships among the evolution of formation of networks of key players; the direction of knowledge flow in these networks; and the timing and stringency of regulatory pressures would significantly advance our understanding of technology-forcing regulations.

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TABLE 1
Key Legislative History for Automobile Emission and Safety Control

Period	Emission Control	Safety
1960s	*The 1965 Clean Air Act Amendments (Motor Vehicle Air Pollution Control Act)* 1. Directed the Department of Health, Education, and Welfare (HEW) to set emission standards for HC and CO emissions for the 1968 model year cars and light-duty trucks.	*The 1966 Motor Vehicle Safety Act (MVSA)* 1. Created the National Highway Safety Bureau (NHSB) 2. The MVSA required NHSB to set standards by Jan. 31, 1968
1970s	*The 1970 Clean Air Act Amendments* 1. Instructed Environmental Protection Agency (EPA) to set standards for HC, CO and NOx for automobiles 2. 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) 3. The NO_x emission standard was set at 0.41g/mi to be met by 1976, which was later revised in 1977	*The Highway Safety Act of 1970* 1. Created the National Highway Transportation Safety Bureau (NHTSA) 2. NHTSA adopted and amended Motor Vehicle Safety Standard 208, Occupant crash protection. NHTSA mandated passive restraints on all vehicles by Jan. 1973, which was delayed to July 1973. The standard also mandated that certified airbags would not inflict certain "injuries" to a 5'9" dummy in a frontal barrier crash at any speed up to and including 30 mph and frontal angles up to 30 degrees.
	The 1977 Clean Air Act Amendments 1. Congress delayed the HC standard until 1980, and the CO and NO_x standards to 1981 (0.41 g/mi for HC, 3.4 g/mi for CO, and 1.0 g/mi for NO_x)	*The Highway Safety Act of 1973* 1. Provided bonus of 25% of federal incentive grant to states that enacted a compulsory seat belt use law. 2. Provided bonus of 25% of federal incentive grant to states achieving major reductions in hwy. death rates.
1980s	*Inspection and Maintenance programs (1983)* 1. Inspection and Maintenance (I/M) programs are established in 64 cities nationwide	*Cancellation (1981) and reinstatement (1984) of passive-restraints rule* 1. Under Reagan Administration regulatory reform, NHTSA canceled passive-restraints standard and called for large-scale safety belt use. 2. The Supreme Court reversed DOT's 1981 revocation of the passive restraints requirements of standard 208 and directed NHTSA to review the case for airbags (1983). 3. NHTSA reinstated the passive-restraints rule requiring passive restraints be installed in 10%, 25%, 40% and 100% of 1987, 1988, 1989 and 1990 and later models respectively (1984).
1990s	*The 1990 Clean Air Act Amendments* 1. Congress required further reductions in HC, CO, NO_x and particulate emissions. 2. Amendments introduced comprehensive programs for; more stringent emission testing procedures; expanded I/M programs; new vehicles technologies & clean fuel programs; transportation management provisions; and possible regulations of emissions from non-road vehicles.	*The Inter-modal Surface Transportation Efficiency Act (ISTEA) (1991)* 1. Requires all passenger cars manufactured on or after September 1, 1997, and light trucks manufactured on or after September 1, 1998, to have drive and passenger airbags, plus manual lap-shoulder belts.
	The National Low Emission Vehicle (NLEV) program (1997) 1. The program is designed to adopt more stringent California LEV program nationwide, started initially with northeast ozone transport regions. 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	*The Transportation Equity Act for the 21st Century (TEA-21) (1998)* Key congressional mandates of TEA-21: 1. Improved protection for all sizes of occupants 2. Airbag systems that minimize risks of death and injury posed by airbags to infants, children and others 3. Protection for unbelted occupants 4. Advanced technologies: TEA-21 authorized NHTSA to require the use of "advanced airbags," which incorporates new technology and engineering beyond the current state of art 5. Rapid phase-in dates requiring advanced airbags must be available as soon as practicable. - Phase-in to begin on September 1, 2002 or no later than September 1, 2003 - Completion of phase-in by September 1, 2005 or by September 2, 2006 (if phase-in began by 2003)

TABLE 2

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, the "Power Plants" includes the subclasses representing "Internal combustion engine with treatment or handling of exhaust gas"
422/174, 179-180	Class 422, the "Chemical apparatus and process 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, the "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, the "Catalyst, solid sorbent, or support therefore: product or process making", include subclasses that represents catalysts comprising a lanthanide series metals or transition metals.
428/116	Class 428, the "Stock materials or miscellaneous articles" include subclass representing honey-comb like structural body for catalytic converters
73/116, 117.3, 118.1	Class 73, the "Measuring and testing" include subclasses representing testing of motor, engine and auxiliary units such as catalytic converter to ensure optimal operations.
29/890	Class 29, the "Metal working" include subclass representing catalytic device making

TABLE 3
Key U.S. Classes and Subclasses for Automobile Safety Technology Patents

Technology Types	USPC Class/Subclasses	Definition of USPC Class/Subclasses
Impact	293/ 2, 102-109, 115-136	Class 293: Vehicle fenders with car control, and buffers and bumper type.
Steering column	74/492-492	Class 74: Machine element and mechanism- Control level and linkage system, steering posts
Seat	297/216.1-216.19	Class 297: Chairs and seats- Crash seat
Seatbelt	242/372-373	Class 242: Winding, tensioning, or guiding-.material engaging, tension responsive etc.,
Airbag	149/1, 10, 45-46 180/116-120	Class 149: Explosive and thermic compositions or charges Class 180: Surface effect vehicles-having propulsion or control means
Theft protection	70/163-166, 184-189 340/ 5.2	Class 70: Locks-external locking device, level carried lock Class 340: Communications, electrical - authorized control-entry into an area.
Warning	116/3	Class 116: Signals and indicators
Brake	188/ 68-75 74/502-506, 512, 516	Class 188: Brakes-wheels Class 74: Machine element and mechanism-foot operated, accelerator, signal,
Tire	152/415-418 340/440	Class 152: Resilient tires and wheels- inflating devices Class 340: Communications, electrical -tilt, imbalance
Head Restraints	297/216.12-216.13	Class 297: Chairs and seats-force absorbing means incorporated into headrest area, into back
Fuel System	137/38-39	Class 137: Fluid handling – control by inertia system

TABLE 4
Descriptive Statistics and Correlations [a, b]

	Variables	Mean	S.D.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	*Patent_Safety*	183.54	124.50														
2.	*Patent_Emission*	67.97	54.94														
3	*Patent_Catalysts* [c]	20.48	10.90		.77*												
4	*Patent_Electronics* [c]	18.52	20.78		.98*	.67											
5	*Patent_Airbags* [d]	69.00	77.52	.98*													
6	*Patent_Seatbelts* [d]	41.51	15.02	.65*				.52*									
7	*Expenditure_Safety* [e]	5.89	0.52	.86*				.87*	.62*								
8	*Expenditure_Emission* [e]	5.61	1.57		.38	.29	.39										
9	*USPatents_Safety*	116.70	95.31	.98*				.99*	.56*	.87*							
10	*USPatents_Emission*	27.90	19.93		.92*	.82*	.86*				.17						
11	*TotalAutoPatents*	1053.19	459.74	.90*	.80*	.65*	.76*	.89*	.60*	.60*	.57	.90*	.72*				
12	*MarketShareForeignFirms*	25.50	11.76	.74*	.63*	.43	.61*	.74*	.55*	.92*	.80*	.74*	.49	.84*			
13	*ForeignPatents_Safety*	66.84	34.87	.87*				.79*	.82*	.70*		.78*		.76*	.62*		
14	*ForeignPatents_Emission*	40.06	37.30		.98*	.69*	.98*				.47			.80*	.66*		

[a] Significant at $p < 0.05$
[b] Correlations of non-interacting variables are omitted in the table
[c] Automobile emissions control technology subsystem
[d] Automobile safety technology subsystem
[e] Logarithm of the expenditures at one year lag

TABLE 5

Regression Coefficients for Negative Binomial Models, Auto Safety & Emission Patent Set

Variable	Dependent Variables					
	PATENT_SAFETY			PATENT_EMISSION		
PATENT_AUTO	0.001	***	(0.000)	0.002	***	(3E-04)
LEXPEN1_Safety	0.356	**	(0.123)			
LEXPEN1_Emission				-0.085		(0.088)
Constant	2.468	***	(0.656)	1.673	***	(0.359)
	Time dummies					
1965	-1.343	***	(0.219)			
1966	-0.677	***	(0.171)			
1967	-0.071		(0.142)			
1968	-0.047		(0.142)	-1.909	*	(0.744)
1969	-			-0.928	*	(0.442)
1970	-0.114		(0.127)			
1971	0.478	***	(0.103)	0.534	*	(0.268)
1972	0.543	***	(0.100)	1.050	***	(0.219)
1973	0.509	***	(0.094)	0.950	***	(0.211)
1974	0.140		(0.103)	1.279	***	(0.195)
1975	-0.117		(0.113)	0.928	***	(0.222)
1976	-0.354	**	(0.124)	1.490	***	(0.275)
1977	-0.460	***	(0.126)	1.378	***	(0.265)
1978	-0.234	*	(0.116)	0.952	**	(0.274)
1979	0.081		(0.107)	0.938	**	(0.287)
1980	-0.169		(0.112)	0.311		(0.295)
1981	-0.341	**	(0.125)	0.281		(0.351)
1982	-0.613	***	(0.134)	0.561	+	(0.31)
1983	-0.610	***	(0.139)			
1984	-0.792	***	(0.134)	-0.247		(0.273)
1985	-0.447	***	(0.117)	-0.491	+	(0.286)
1986	-0.250	*	(0.111)	0.129		(0.273)
1987	-0.624	***	(0.124)	-0.118		(0.235)
1988	-0.470	***	(0.110)	-0.078		(0.21)
1989	-0.128		(0.093)	0.042		(0.216)
1990	-0.063		(0.089)	0.574	**	(0.196)
1991	-0.017		(0.094)	1.011	***	(0.185)
1992	-			1.300	***	(0.202)
1993	0.143		(0.091)	1.351	***	(0.177)
1994	0.164	*	(0.079)	0.936	***	(0.134)
1995	0.162	*	(0.079)	0.761	***	(0.12)
1996	0.213	**	(0.078)	0.572	***	(0.118)
1997	0.236	**	(0.068)	0.240	*	(0.109)
1998	0.184	**	(0.070)			
1999	0.238	***	(0.068)			
2000	0.121	+	(0.065)			
Pseudo R2	0.434			0.453		
Log Likelihood	-126.43			-87.96		
N	6357			2108		

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

TABLE 6

Regression Coefficients for Negative Binomial Models, Key auto emissions subsystems' patents: catalysts & electronics

Variable	Dependent Variables					
	Catalysts			Electronic Feedback Contr		
PATENT_AUTO	0.001	**	(0.000)	0.003	***	(1E-03)
LEXPEN1_Emission	0.004		(0.109)	0.013		(0.345)
Constant	1.601	**	(0.502)	-2.384		(1.552)
	Time dummies					
1968	-1.449	+	(0.775)	-		
1969	-			-		
1970	-			-		
1971	-0.099		(0.434)	1.744	+	(1.003)
1972	1.024	**	(0.308)	2.131	*	(0.841)
1973	1.138	***	(0.292)	1.640	*	(0.821)
1974	0.934	**	(0.280)	2.388	**	(0.703)
1975	0.578	+	(0.316)	1.979	*	(0.763)
1976	0.884	*	(0.344)	3.025	**	(0.908)
1977	0.755	*	(0.339)	2.731	**	(0.872)
1978	0.432		(0.356)	1.968	*	(0.883)
1979	0.036		(0.406)	1.878	*	(0.929)
1980	0.038		(0.381)	0.201		(1.055)
1981	-0.117		(0.446)	1.570		(1.039)
1982	-0.113		(0.425)	-0.385		(1.342)
1983	-			-		
1984	-0.144		(0.350)	-0.283		(0.866)
1985	-0.796	+	(0.433)	-0.105		(0.809)
1986	0.304		(0.329)	0.238		(0.882)
1987	-0.108		(0.324)	-0.357		(0.757)
1988	0.282		(0.272)	-0.917		(0.762)
1989	0.368		(0.275)	-0.253		(0.699)
1990	0.459	+	(0.271)	0.826		(0.612)
1991	0.668	*	(0.260)	1.681	**	(0.585)
1992	0.667	*	(0.280)	2.088	**	(0.664)
1993	0.115		(0.299)	2.182	***	(0.574)
1994	0.201		(0.252)	1.464	***	(0.381)
1995	0.280		(0.236)	1.077	***	(0.307)
1996	0.293		(0.232)	0.982	***	(0.272)
1997	0.236		(0.235)	0.185		(0.193)
1998	-			-		
Pseudo R2	0.405			0.500		
Log Likelihood	-71.12			-60.63		
N	635			574		

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

TABLE 7

Regression Coefficients for Negative Binomial Models, Key auto safety subsystems' patents: airbag & seatbelt

Variable	Dependent Variables					
	Airbag			Seatbelt		
PATENT_AUTO	0.005	***	(0.0002)	0.001		(0.0001)
LEXPEN1_Safety	0.907	***	(0.227)	0.386		(0.281)
Constant	-1.819		(1.267)	0.943		(1.485)
	Time dummies					
1965	-			-0.953	*	(0.414)
1966	-2.402	**	(0.736)	-0.084		(0.314)
1967	0.027		(0.293)	-0.038		(0.31)
1968	-0.082		(0.302)	-0.025		(0.309)
1969	-			-		
1970	0.183		(0.238)	-0.437		(0.314)
1971	0.969	***	(0.189)	0.414	+	(0.234)
1972	0.769	***	(0.193)	0.694	**	(0.216)
1973	0.398	*	(0.191)	0.886	***	(0.195)
1974	-0.481	*	(0.237)	0.795	***	(0.195)
1975	-0.706	**	(0.256)	0.544	**	(0.21)
1976	-1.597	***	(0.375)	0.439	*	(0.219)
1977	-1.338	***	(0.325)	0.338		(0.22)
1978	-1.02	***	(0.286)	0.466	*	(0.211)
1979	-0.991	**	(0.286)	0.827	***	(0.197)
1980	-1.243	***	(0.314)	0.637	**	(0.2)
1981	-1.466	***	(0.357)	0.315		(0.228)
1982	-1.223	***	(0.314)	0.147		(0.231)
1983	-2.556	***	(0.591)	0.318		(0.229)
1984	-1.538	***	(0.341)	-0.008		(0.234)
1985	-1.909	***	(0.4)	0.504	*	(0.202)
1986	-1.172	***	(0.296)	0.603	**	(0.196)
1987	-1.497	***	(0.329)	0.164		(0.223)
1988	-0.823	***	(0.231)	0.214		(0.206)
1989	-0.299	+	(0.176)	0.41	*	(0.183)
1990	0.091		(0.145)	0.166		(0.194)
1991	0.007		(0.141)	0.261		(0.206)
1992	-			-		
1993	0.27	*	(0.133)	-0.141		(0.231)
1994	0.249	*	(0.116)	0.123		(0.194)
1995	0.295	*	(0.115)	-0.024		(0.204)
1996	0.22	+	(0.115)	-0.046		(0.204)
1997	0.278	**	(0.099)	0.232		(0.174)
1998	0.287	**	(0.102)	0.216		(0.179)
1999	0.354	***	(0.097)	0.103		(0.182)
2000	0.103		(0.093)	0.4	*	(0.172)
Pseudo R2	0.497			0.342		
Log Likelihood	-97.04			-101.474		
N	2342			1483		

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

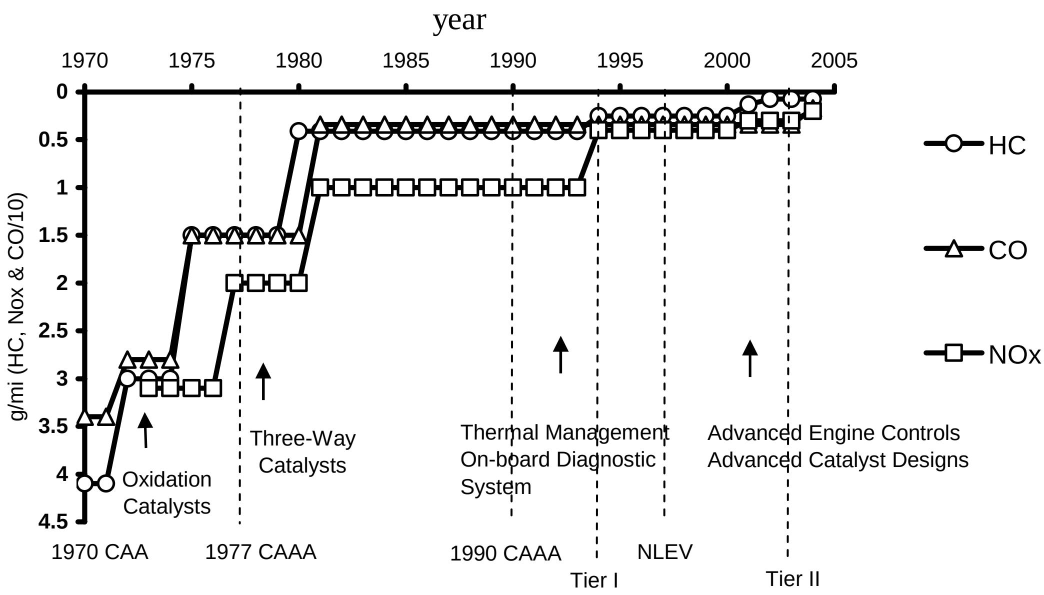
TABLE 8
Regression Coefficients for Negative Binomial Models, U.S. firms' patents

Variable	Dependent Variables				
	PATENT_SAFETY _USFIRMS			PATENT_EMISSION_USFIRMS	
MS_FOREIGN	-0.057	***	(0.013)	0.01558	(0.018)
PATENT_FOREIGN	0.009	***	(0.002)	0.00967 **	(0.004)
PATENT_AUTO	0.0002		(0.0003)	0.0003	(0.000)
LEXPEN1_Safety	2.239	***	(0.233)		
LEXPEN1_Emission				-0.05931	(0.092)
Constant	-8.301	***	(1.247)	2.4513 ***	(0.445)
			Time dummies		
1965	-				
1966	0.751	**	(0.255)		
1967	1.215	***	(0.214)		
1968	0.995	***	(0.203)	-1.9306 *	(0.750)
1969	0.697	**	(0.204)	-0.89378 +	(0.479)
1970	1.130	***	(0.192)		
1971	0.688	***	(0.128)	0.55696 +	(0.298)
1972	0.419	**	(0.129)	0.93461 ***	(0.255)
1973	-			0.74207 **	(0.272)
1974	-0.191		(0.138)	0.80375 **	(0.241)
1975	-0.333	*	(0.157)	0.10853	(0.271)
1976	-0.703	***	(0.185)		
1977	-0.158		(0.175)	-0.05011	(0.299)
1978	0.330	*	(0.162)	-0.4784	(0.362)
1979	-0.112		(0.171)	-0.08588	(0.295)
1980	0.428	*	(0.189)	-0.57994	(0.355)
1981	-			-0.86433 *	(0.425)
1982	0.122		(0.234)	-1.15328 **	(0.442)
1983	0.107		(0.234)	-0.39494	(0.380)
1984	0.006		(0.223)	-0.59109	(0.386)
1985	0.190		(0.195)	-0.97315 *	(0.438)
1986	0.457	*	(0.197)	-0.31936	(0.326)
1987	0.694	**	(0.239)		
1988	0.495	*	(0.191)	-0.12457	(0.303)
1989	0.364	*	(0.154)	-0.26787	(0.299)
1990	0.506	**	(0.153)	-0.02933	(0.233)
1991	0.044		(0.135)	0.52816 **	(0.188)
1992	0.269	+	(0.142)		
1993	0.168		(0.117)	0.15672	(0.201)
1994	0.374	***	(0.095)	-0.20743	(0.202)
1995	-			0.01069	(0.176)
1996	-0.135		(0.093)	-0.34431 +	(0.190)
1997	-0.004		(0.078)		
1998	-0.044		(0.080)	-0.16484	(0.188)
1999	-0.227	*	(0.094)		
2000	-0.110		(0.081)		
Pseudo R2	0.444			0.427	
Log Likelihood	-116.59			-75.487	
N	4022			865	

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

FIGURE 1

Federal Automotive Emission Standards for the Period 1970 to 2004 and Introduction of Emission Control Technologies



The permitted emission levels of all three critical pollutants decreased throughout the seventies. By 1981, emission requirements had reached one tenth of the original 1970 value. Increased stringency is again observed in 1994 with the implementation of the Clean Air Act Amendments of 1990 (1990CAAA). Automobile manufacturers faced nationwide implementation of National Low Emission Vehicle (NLEV) program in 2001 and Tier II standards in 2004. As stringency increased, the automotive industry introduced new emission control technologies. Source: (Lee 2004).

FIGURE 2

Patent Trend in Automobile Emission Control and Safety: 1965 - 2002

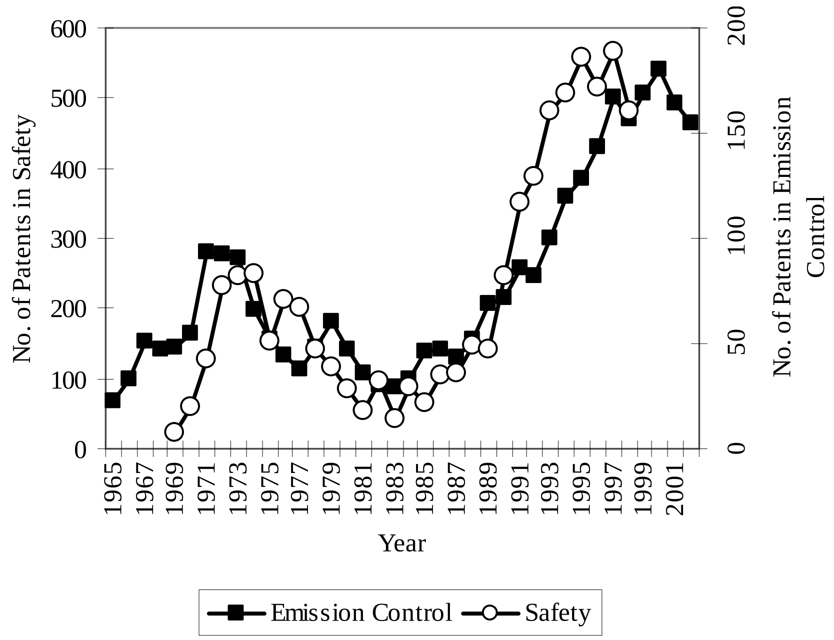
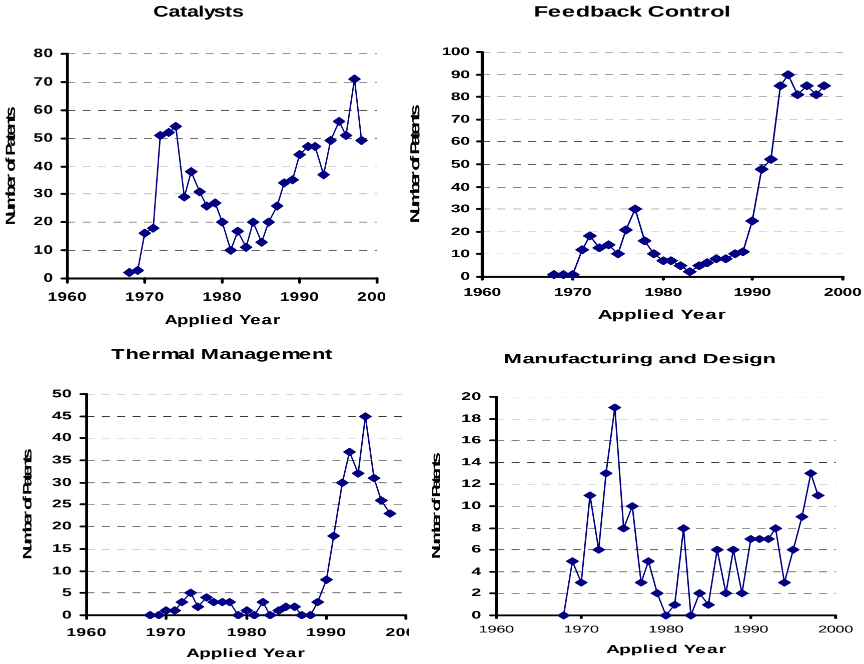
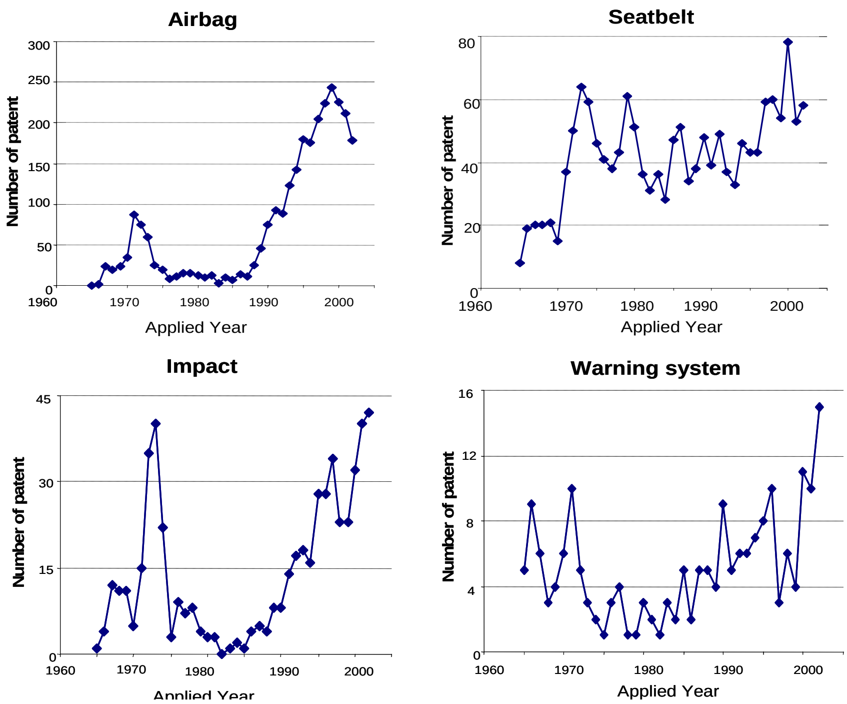


FIGURE 3

Patenting activities in automobile (a) Emissions control and (b) Safety technologies in four sub-technology categories



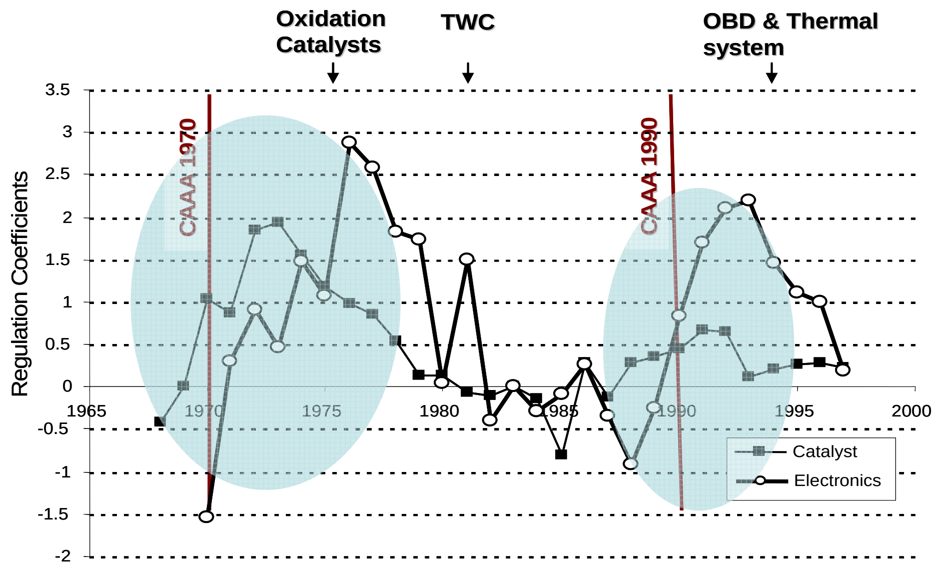
(a)



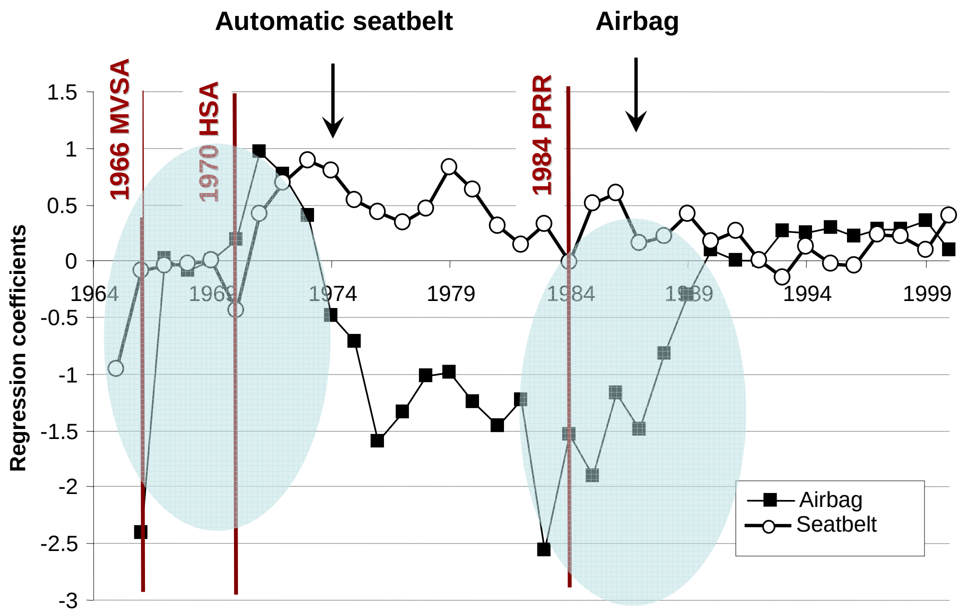
(b)

FIGURE 4

Regression coefficients for year dummy variables: (a) Emission control and (b) Safety automobile sub-technology systems.



(a)



(b)

CAAA1970: the Clean Air Act Amendments in 1970
CAAA1990: the Clean Air Act Amendments in 1990
1966 MVSA: Motor Vehicle Safety Act of 1966
1970 HAS: the Highway Safety Act of 1973
1984 PRR: Reinstatement of Passive Restraints Rule of 1984