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Forcing technological change: A case of automobile emissions control technology development in the US

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ABSTRACT

This article investigates how regulated automakers and upstream component suppliers comply with "technology-forcing" regulations, or laws that set performance standards beyond their usual technological capabilities. In particular, this article examines how firms manage and organize their research and development (R&D) processes concerning automobile emissions control technologies amid the uncertainties resulting from the issuance of new regulations. This study involves the analyses of patents, interviews with experts, references to technical papers published for conferences of the Society of Automotive Engineers (SAE), and use of learning curves. The results of this study show that the high regulatory standards under the technology-forcing regulation played an important role in forcing technological innovations and determining subsequent direction of technological change. Component suppliers were important sources of innovation in the 1970s, but over the course of technological evolution, automakers gradually emerged as the locus of innovation. This study also shows that firms strategically manage architectural and component knowledge in the presence of uncertainties about their technological capacity to meet new auto emissions control standards.

1. Introduction

"Technology-forcing" regulations are those that mandate firms to meet performance standards that go beyond the existing technical capabilities of the industry or to adopt specific technologies that have not been fully developed (Jaffe et al., 2002). The development of substitutes for chlorofluorocarbons (CFCs) is one of the popular success stories about technological innovation that is done in compliance with technology-forcing regulations (Ashford et al., 1985; McFarland, 1992). Banning the use of halogenated chlorofluorocarbons (CFCs) found in aerosol applications by the Consumer Product Safety Commission (CPSC) and the Environmental Protection Agency (EPA) under the Toxic Substances Control Act (TSCA) resulted in two innovations: non-fluorocarbon propellants and a new pumping system which do not only eliminate CFCs but also do so in a way that is more affordable than that of the original system (Ashford et al., 1985). Although technology-forcing regulations that require the adoption of specific technologies have often been criticized for discouraging innovation (Magat, 1979; McGarity, 1994; Jaffe et al., 2002), recent studies that have examined the development of flue gas desulfurization (FGD) systems for SO_2 control in the power sector showed the significant influence of technology-based regulatory standards on technological innovation (Popp, 2003; Taylor et al., 2005). Using carefully screened patent data as an indicator of innovation, Taylor et al. (2003, 2005) showed that the level of innovative activities in FGD technology increased with the passage of the New Source Performance Standards (NSPS) in 1979. The New Source Performance Standards which served as an example of technology-based standard required SO_2-emitting firms in the power sector to install FGD systems with a 90% SO_2 removal efficiency.

Despite this recent evidence, scholars have generally been skeptical about the effectiveness of the command-and-control type of technology-forcing regulations as a driver of innovation (Jaffe et al., 2002; Bansal and Gangopadhyay, 2005). When technology-forcing regulations are enacted, firms usually do not immediately get information about the cost of compliance and the availability of the new technological solutions they need to develop (Miller, 1995; Kemp, 1997; Gerard and Lave, 2005). Developing technologies that meet regulatory standards can be

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costly. Moreover, even a concerned regulatory agency may not have an accurate assessment of the innovative capacity of a target industry (Ashford et al., 1985). Uncertainties exist not only about the availability of technological solutions necessary to satisfy regulatory demands, but also about a regulatory agency's capability to enforce the regulatory standards it set (Bansal and Gangopadhyay, 2005; Gerard and Lave, 2005; Mohr, 2006; Mickwitz et al., 2008). Poor credibility of a regulatory agency as far as enforcing the standards are concerned may encourage firms to behave strategically, such as by influencing the regulator to be less strict in the enforcement of the standards or to encourage it to delay enforcement (Lutz et al., 2000; Puller, 2006).

Literature in operations and supply-chain management also addresses new and emerging challenges in integrating firms' needs for sustainability with their existing business practices (Kleindorfer et al., 2005; Seuring and Muller, 2008). Firms are increasingly pressured to embrace sustainable operations under the triple-bottom line approach, which requires firms to achieve a certain level of performance in the environmental, economic, and social dimensions (Elkington, 1998). Moreover, sustainable supply-chain management is critically related to external pressures and to incentives given by different groups, such as government, customers, and stakeholders (Linton et al., 2007; Seuring and Muller, 2007). In particular, this movement towards integrating sustainable operations with legislation requires firms to engage in sustainable supply-chain management, under which focal firms evaluate risks and performances of suppliers based on environmental and social criteria (Seuring and Muller, 2008). However, the relationship among regulatory pressures, firms' operations, and supply chain is not well established in the literature.

This paper aims to address the need to enhance understanding of the processes in the auto industry in response to pressures created by the issuance of technology-forcing regulations. This paper attempts to meet the objective by examining a case of technological innovation, particularly the development of automobile emissions control technologies. Innovation in automotive emissions control technologies provides a very interesting case for understanding the responses of firms to technology-forcing regulations for several reasons. First, automotive emissions control regulations represent key regulatory events that forced technological innovation since these require performance standards that are clearly beyond the technical capability of the industry (Leone, 1986). As a result of regulatory actions since the late 1960s, cars today are equipped with emissions control devices that can reduce the amount of automobile emissions by more than 95% from that seen in the early 1970s (Bertelsen, 2001). More interestingly, automotive emissions control technologies represent a set of technologies that is more complex than the previously studied cases of CFC phase-out or flue gas desulfurization systems used for SO_2 control in electric power plants. Automotive emissions control technologies consist of multiple components such as catalysts, electric feedback control, and thermal management systems. The development of each component itself requires a multiple number of firms to supply sub-units, encouraging a more in-depth analysis of how key innovating players, such as automakers and major component suppliers, responded to the technical challenges and uncertainties created by imposition of technology-forcing regulations. Furthermore, prior studies that relied on industry-level data were constrained by the aggregate nature of their data (Jaffe and Palmer, 1997). Thus, a firm-level analysis in a focused industry study, such as the development of emissions control technologies in the auto industry, may provide a better understanding of the nature of the relationship between regulation and innovation.

This research also identifies major innovators of automobile emission control technologies by analyzing patents and technical articles cited by relevant patents. While it is apparent that new technologies were being generated as a result of regulations, sources of knowledge about how these new automotive emission control technologies were innovated are unknown. Ashford et al. (1985) suggested that the regulated industry and the pollution control industry are the types of industrial sectors that respond to environmental regulations. The regulated industry and pollution control industry will likely introduce new processes, new devices, and/or product substitutions (Ashford et al., 1985). In the automotive sector, regulated firms, such as automotive manufacturers, and components suppliers specializing in manufacturing pollution control devices, contributed the major portions of the innovations of these technologies. However, the respective degrees to which firms from a regulated industry and their pollution control equipment suppliers contributed to total innovation are not clear. Further, there is possibility that the knowledge credited for the innovations could have originated from other institutions other than those of the regulated and pollution control industries. Private and government-funded research institutions, as well as universities, could have also contributed the knowledge base for intellectual property for the development of automobile emission control technology. In fact, prior studies on the impact of public R&D on industrial innovation (e.g., Cohen et al., 2002) showed that the role of public R&D on industrial innovation has expanded over the last three decades. A better understanding of these issues will deepen the understanding of the processes by which "forced" innovation drives learning and technology-upgrading processes in a distributed innovation environment.

This study focuses on the period from 1970 to 1998.[4] This period captures the key regulatory actions in the history of automobile emissions control regulations such as the Clean Air Act Amendments in 1970 (1970CAAA) and in 1990 (1990CAAA). The research questions that we want to explore in this research are the following: Did government actions, from merely threatening to impose regulations to the actual imposition of increasingly stringent ones, actually influence the innovative activities of automakers and their suppliers? If so, where does the technology come from? Who were the key contributors? Moreover, this study also aims to know how "learning" takes place during the process of technological development under technology-forcing regulatory regimes. This research, in attempting to answer these questions, incorporates well-established quantitative and qualitative methods in the mainstream innovation literature. We analyzed carefully screened US patents in auto emissions control technologies, relevant technical papers published in the Society of Automotive Engineers (SAE) conference proceedings, and cost trends in emissions control devices. Furthermore, we interviewed various experts in the fields to complement the findings of this study.

The paper is organized as follows. It begins with an overview of technology-forcing regulations and innovation in automobile emissions control technologies. It then describes the methods used to develop the relevant patent set, technical publications database, and cost data. The findings of this study are subsequently presented. The paper concludes with a discussion on the impact of the command-and-control type of technology-forcing regulations on technological change, and the different and evolving roles of automakers, suppliers, and other institutional

[4] This research is based on a historical analysis of technological change in the US auto industry. Hence, the case considered here probably does not necessarily have a direct relevance for toda US automotive industry, which is very different and undergoing a period of great difficulties. Still, we believe our findings provide relevant insights, even if only considered indirectly.

players such as universities and research institutes as the sources of innovation during the technology-forcing regulatory era.

2. Overview of technology-forcing regulations and innovation in auto emissions control

2.1. Government regulations

From the 1950s, emissions from automobiles were believed to be a major source of the pollutants responsible for smog problems in southern California. To address the problem, in 1961, the automotive industry voluntarily installed positive crankcase ventilation devices on all cars sold in California to reduce blow-by emissions. However, automakers did not actively seek to develop other emissions control devices that could further reduce harmful emissions from their automobiles (White, 1982). Given this backdrop, the legislature in California set up the California State Motor Vehicle Pollution Control Board in 1961 and established a driving test schedule for measuring emissions (Mondt, 2000). Following California's legislature, the Congress passed amendments to the Clean Air Act (CAA) in 1965, authorizing the Department of Health, Education, and Welfare (HEW) to set automotive emissions standards (Lave and Omenn, 1981). The HEW subsequently set emissions standards for hydrocarbons (HC) and carbon monoxide (CO) for 1968 model-year cars and light-duty trucks.

The 1970CAAA was an important step in the history of automobile emissions control. A summary of the critical regulations is provided in Table 1. The newly created Environmental Protection Agency (EPA) targeted that by 1975, a 90% reduction of HC and CO emissions from the levels seen in 1970 should have been achieved. The EPA also ordered that by 1976, a 90% reduction of nitrogen oxide (NO_x) levels seen in 1971 should have been achieved (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. The law's enactment was strongly opposed by automakers. As a result, the timetable for the attainment of the emission reductions was, therefore, delayed several times. In 1973, intermediate emissions standards were set for the 1975 car models. The 90% emissions reduction requirement for HC was deferred to 1980, and the requirements for CO and NO_x were deferred to 1981 by the 1977 Clean Air Act Amendments (1977CAAA) (White, 1982). The 1977CAAA also reduced the NO_x emissions requirement to 1.0 g/mile.

No further emissions reduction requirements were set until the late 1980s. In 1988, California passed its own Clean Air Act, which required reductions from the 1987 levels of volatile organic compounds (VOC) and NO_x by 55% and 15%, respectively (NESCAUM, 2000). Following the California lead, the Congress amended the Clean Air Act in 1990 (the 1990CAAA), requiring reductions from the 1990 levels of HC and NO_x of 35% and 60%, respectively, by 1994 (Tier I standard) (NESCAUM, 2000). The EPA set even more stringent standards in 1999 to be phased in between 2004 and 2009 (Bertelsen, 2001). These "Tier II" standards were similar to California's LEV II (Low Emission Vehicle II) program standards adopted in 1998, and required reductions in HC and CO emissions of 98% and 95%, respectively, from the levels seen in 1965 (NESCAUM, 2000).

The National Low Emission Vehicle (NLEV) program was established in 1997 between the imposition of Tier I and Tier II standards. It aimed to adopt California's LEV program and apply it throughout the northeast Ozone Transport Region (EPA, 1997). Under the NLEV program, automakers had the option of complying with the program, whose standards were more stringent those of Tier I. Once the automakers were committed to the program, they had to meet the standards in the same manner as other federal emissions requirements (EPA, 1997).). In return, the EPA would provide regulatory stability and reduce regulatory burdens by harmonizing federal and California standards (EPA, 1997). Although they could choose not to, the automakers nonetheless complied with the program because they wanted a stable regulatory environment. The NLEV program continued through 2003 and was replaced by the Tier II program afterward (Bertelsen, 2001).

The NLEV standard required automakers to introduce cleaner vehicles in mandated ozone transport regions before nationwide vehicle introductions in 2001 according to the following schedule: 40% transitional-low-emission-vehicles (TLEV), 30% LEV, and 30% Tier I vehicles of 1999 model and 40% TLEV and 60% LEV by 2000.

Table 1
Government actions with potential impacts on patenting activities.
Source: EPA (1997) and Mondt (2000).

Government actions	Summary
1970 Clean Air Act (1970CAAA)	The Act called for 90% reductions in automotive emissions: hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxide NO_x. HC and CO reduction level was set at 0.41 g/mi and 3.4 g/mi, respectively, for new automobiles in 1975. The NO_x emissions standard was set at 0.41 to be met by 1976, which was later revised in 1977
1977 Clean Air Act Amendment (1977 CAAA)	The Congress delayed the HC standard until 1980, and the CO and NO_x standards to 1981; the 1981 NO_x standard was relaxed to 1 g/mi
1990 Clean Air Act Amendment (1990CAAA)	The Congress required further reductions in HC, CO, NO_x, and particulate emissions. Moreover, the amendments introduced a comprehensive set of programs aimed at more stringent emissions testing procedures, expanded I/M programs, new vehicles technologies and clean fuel programs, transportation management provisions, and possible regulation of emissions from non-road vehicles
National Low Emission Vehicle Program (NLEV)	The program was designed to adopt a more stringent California LEV program nationwide, which started initially with the northeast ozone transport regions 1999: 40% TLEV, 30% LEV, 30% TIER 1 2000: 40% TLEV, 60% LEV 2001: LEV standard Moreover, automakers have the option of not complying with the NLEV program, yet they have agreed to comply with this program as EPA and the states indicated that they would provide them with regulatory stability NLEV continued through MY2003 after it was replaced by Tier 2 standard

Tier 1: 0.25 g/mi HC, 3.4 g/mi CO, 0.4 g/mi NO_x.
TLEV (Transitional Low Emission Vehicle): 0.125 g/mi NMOG, 3.4 g/mi CO, 0.4 g/mi NO_x.
LEV (Low Emission Vehicle): 0.075 g/mi NMOG, 3.4 g/mi CO, 0.2 g/mi NO_x.

2.2. Innovation in automobile emissions control technologies

The three major pollutants from Otto cycle automobile engines are hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x). The formation of automobile emissions stems mainly from the incomplete combustion of the fuel during normal engine flame propagation processes. The automotive emissions control devices, which was used prior to the introduction of catalytic converters in 1975 included positive crankcase valve (PCV) systems, evaporation-control systems (ECS), transmission control spark (TCS), thermovacuum switch (TVS), air-injected reactor (AIR), and exhaust gas recirculation (EGR) (Patterson and

Henein, 1972; Mondt, 2000). These systems controlled automobile emissions in principle, by modifying existing engine systems (Mondt, 2000).

Initially, automakers modified existing engine architectures to satisfy emission reduction requirements mandated under the 1970CAAA using technologies such as exhaust gas recirculation (EGR), thermal vacuum switch (TVS), lean and rich thermal reactors, and air preheat system (THERMAC) rather than installing an add-in type catalytic converter, which required extensive knowledge about catalysts that these firms did not possess. For the automakers, a catalyst-based emission control system would represent a competence-destroying rather than competence-enhancing technological discontinuity (Tushman and Anderson, 1986) because emissions reduction by catalysts would make obsolete most engine modification technologies possessed by automakers. Honda's compound vortex controlled combustion (CVCC) engines and Chrysler's lean-burn engines satisfied the 1975 EPA's requirements for HC and CO reduction levels of 1.5 g/mi and 15 g/mi for HC and CO, respectively (Dexter, 1979; Doyle, 2000) without using catalytic converters, and these engines exemplify the incumbent firms' inclination to rely on its existing expertise when faced with technological threats (Cooper and Schendel, 1976). Honda's and Chrysler's engines, however, soon became obsolete when the nitrogen oxide (NO_x) reduction requirements originally stipulated under the 1970CAAA were implemented in 1981. Add-in type converters with catalysts became the only viable technical solutions for simultaneously reducing all three pollutants: HC, CO, and NO_x.

Realizing that a combination of prior emissions control technologies that relied on engine modifications was not sufficient to meet the required emissions stringencies for oxide (NO_x) reduction requirements, catalytic converter technology became the only feasible technology capable of reducing all three major pollutants (Mondt, 2000; Nill and Tiessen, 2005). The first-generation of catalytic converter introduced in 1975 was mainly based on an oxidation catalyst specifically focused on abating HC and CO. The second generation of catalysts appeared when the reduction level of 1.0 g/mi for NO_x had to be met starting in 1981. The first solution to this task was to use the dual-bed catalytic converter design, under which the NO_x catalysts were placed upstream of the air injection system in the exhaust and the oxidation catalyst (Heck and Farrauto, 2002). The engine operates in a rich fuel-air mixture for the reduction of NO_x, and air is blown into the exhaust stream before it reaches the oxidation catalyst to promote the oxidation of CO and HC in the stream. The three-way catalyst appeared to facilitate the simultaneous removal of all three pollutants, and it eliminated the need for a two-staged dual-bed catalytic converter and the air injection system (Heck and Farrauto, 2002). The need for a precise control of air-to-fuel ratio of around 14.5 to achieve simultaneous conversion of all three pollutants stimulated the development of the electronic feedback control system, which included the oxygen sensor and the control module.

In the 1990s, the automobile industry introduced even more sophisticated emissions control devices such as electronically controlled air-to-fuel injectors, electronic exhaust gas recirculation (EGR), fast-response temperature sensors, rapid catalyst warm-up systems, and combined NO_x/O_2 sensors to meet the even more stringent requirements of the Clean Air Act Amendments of 1990 (Bertelsen, 2001).

3. Methods

Three types of data were utilized for the analysis: US patent data set, technical papers published by the Society of Automotive Engineers (SAE) special series publications (SP), and cost data set for automobile emissions control devices compiled from various sources. We also carried out extensive interviews with industry experts involved in the development of automobile emissions control technology to strengthen the study. Rigorous empirical analyses using patents, technical publications, and costs data, together with extensive interviews with experts helped us gain a better understanding of the nature, and extent of the underlying scientific and technological efforts that supported innovations.

3.1. Data

3.1.1. Patent database

The relevant patent set was developed using patent data from the US Patent and Trademark Office (USPTO). Two approaches were used to generate the relevant patent set: an abstract-based keyword search and a class-based search. For the abstract-based keyword search, seven different key words were selected based on the author's understanding of relevant technologies: catalytic converters, emission, automobiles, catalysts, pollution, exhaust, and engines. These keywords were then arranged in different combinations to obtain the patent set electronically. Duplicate patents were eliminated, and irrelevant patents were also removed by reading through the abstracts of screened patents. Sometimes, it was necessary to examine the "Assignee" and "Claims" portion of the patent because catalytic converter technologies can be related to non-automobile technologies such as stationary electric power plants. A close examination of such patents was necessary. A class-based search method was also carried out to generate the patent set. The patent subclasses representing catalytic converter technology were adopted from prior patent studies on automotive catalytic converter technology by Battell Research (Campbell and Levine, 1984). Battell's research on patenting activities in catalytic converter technologies used patent subclasses within two patent classes: Class 55—Gas Separation and Class 423—Inorganic Chemistry. Class55/Dig30 represents the internal structure and control systems used with catalytic converters, and subclasses 212, 213.2, 213.5, and 213.7 within Class 423 represent mostly chemical automotive patents dealing with the chemical composition of the catalyst or its supporting materials (Campbell and Levine, 1984). The process for obtaining the relevant patents using class-based searching was similar to that of abstract-based keyword search: the patents were pulled from each subclass, duplicate patents were eliminated, relevant patents were identified by reading through the abstracts and the "Claims" portion, and assignee sections were examined, if necessary, to sort out technologies unrelated to automotive emissions controls.

The patents from these two different search methods were combined, and those duplicate patents found by each method were eliminated. Information on grant and application dates, assignee, and country of origin was extracted to construct a time-series patent database in automotive emissions control technologies. We identified a total of 2253 automotive emissions control-related patents for the period between 1970 and 1998.

3.1.2. Technical publications database

SAE SP series publications were thoroughly searched to identify SAE SP publications in automobile emissions control technologies. The published papers in the identified SP series were further screened by reading through their abstracts. We then constructed a technical paper database by coding authoring institutions and published years for the identified papers. We identified a total of 701 SAE technical papers published between 1970 and 1998.

3.1.3. Cost database

We built the cost database for automobile emissions control devices using two main sources: the EPA (1990) and the California Air Resource Board (CARB, 1996). The EPA (1990)'s study provides the aggregated cost estimates for emissions control systems from 1972 to 1993 and the CARB's study provided estimates for the additional costs required to comply with the more stringent regulatory standards imposed under to the introduction of the Clean Air Act of 1990 and LEV standards (CARB, 1996). CARB's cost estimates are based on a detailed breakdown of the components of more advanced emissions control technologies that included universal exhaust oxygen sensors, full electronic EGR systems, close-coupled catalysts, electrically heated catalysts, leak-free exhaust systems, engine modifications such as improved piston ring and head gasket design, and electric air injection systems.

3.2. Expert interviews

Experts in automotive emissions control technologies were interviewed to complement the empirical analysis of patents and SAE technical papers. The opinions expressed by the experts may provide rich insights that can be used not only to verify empirical findings from the statistical analysis but also as sources of additional information, especially on intra-organizational activities and the industrial-innovation environment.

To identify the experts, the session chairs in automotive emissions control technologies at SAE conferences were examined. Session chairs were primarily chosen as the main target population because they are presumed to represent the key individuals who are active in research in automotive emissions control technologies. The organizational affiliations of the selected session chairs were closely examined to ensure that the selected experts represent a number of different organizations. Some of experts interviewed even referred other experts, who possessed excellent career backgrounds to qualify them as the key experts to aid in the attainment of the objectives of this research.

4. Results

4.1. Inventive activities: timing of technology introductions and patenting trend

First, one can look at how the introduction of critical new technologies is related to the timing of the enactments of federal regulations. For this analysis, a series of onset of automotive emissions control regulations and corresponding levels of stringencies for each of the three major pollutants is mapped against the introduction of critical new technologies. Fig. 1 shows the emissions standards from 1970 to 1998 for HC, CO, and NO_x. It is easy to see the evolution of standards, which became notably more stringent in 1975 and 1981 following the enactment of the 1970CAAA. The permitted emission levels for all three pollutants in 1970 decreased to one-tenth by 1981. Standards then remained stable until 1994, when the Tier I standards set by the 1990CAAA were implemented. The standards tightened again in 2001, reflecting the phase-in of Tier II standards in 2004.

As shown in Fig. 1, the automotive industry launched new emissions control technologies whenever increasingly more stringent regulatory standards phased-in: oxidation catalysts in 1975, three-way catalysts in 1981, and thermal management and onboard diagnostic systems in 1994. The auto industry also introduced more advanced catalyst technologies such as high-density and hexagonal cell-structured catalyst support, and engine control systems such as electronic-controlled exhaust gas recirculation and fuel injectors with improved fuel atomization, to satisfy even more stringent Tier II standards (Bertelsen, 2001).

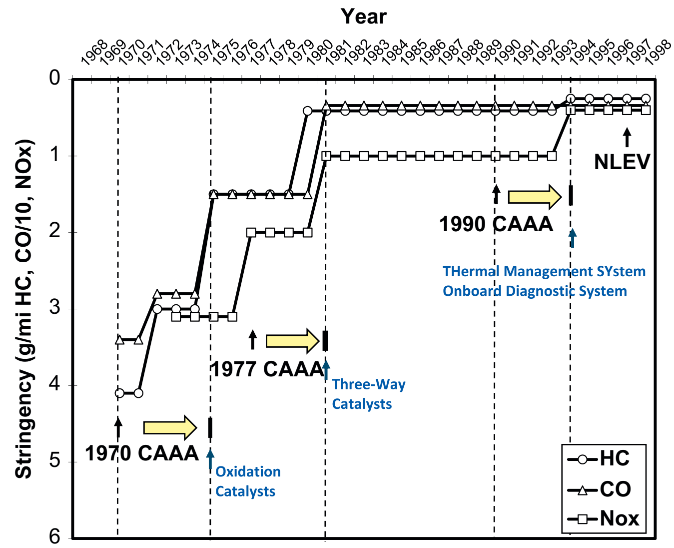


Fig. 1. Federal automotive emissions standards, 1970–1998.

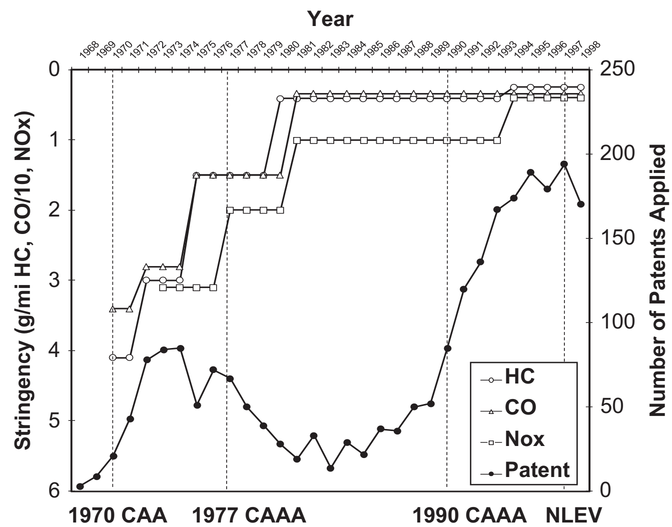


Fig. 2. Regulation stringency levels and patenting activities in automotive emissions control technologies, 1970–1998.

A second analysis, shown in Fig. 2, contrasts time-series with the magnitudes of patenting activities with the same series of stringency levels for each of the three major pollutants presented in Fig. 1. Fig. 2 suggests that an increase in stringency leads to an increase in patenting activity. The phasing-in of the 1975 intermediate emission standards and the 1981 emissions standards was followed by an increase in patenting activities in the early and mid-1970s. A similar observation was seen in the late 1980s when patenting activity rose steeply, coinciding with the phasing-in of more stringent emission standards in 1994 as a result of the 1990CAAA. The extended period of decline in patenting activities that began in the mid-1970s also provided additional evidence of the close relationship between government regulations and innovative activities. Results of this study suggest that firms, once they realized that the Congress would probably pass the 1977CAAA, reduced the intensity of their innovative activities. Hence, we see a reduced patenting activity from 1975 to 1981. This observation is not surprising given that the

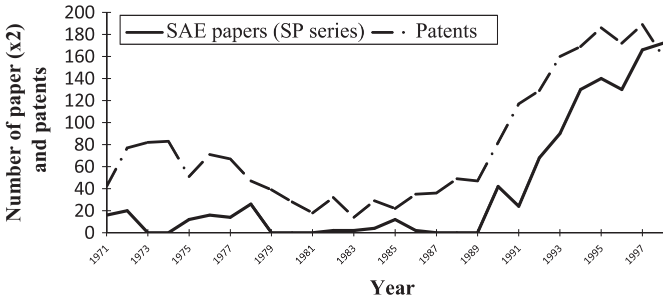


Fig. 3. Patents and SAE publications in the automobile emissions control from 1970 to 1998.

1977CAAA was enacted to delay the imposition of the 90% emissions reduction requirements. The industry probably had been developing three-way catalyst (TWC) technologies in the early to mid-1970s before the passage of the 1977CAAA; however, the industry believed that a TWC system, although it would meet the more stringent requirement of the 1970CAAA, could not be perfected in time to meet the original schedule. Magnitudes of publishing activities from 1970 to 1998 are shown in Fig. 3. Fig. 3 shows that both the patenting and publishing activities follow very similar pattern over the course of AECS' development.

These data also clearly suggest that the firms affected by regulatory measures innovated (i.e., carried out R&D, invented something "new and non-obvious," submitted patent applications on their inventions, and obtained those patents when issued) every time new emission standards were set. An analysis of the nature of the patents (by reading abstracts and claims) clearly suggests that the firms worked on the various technological elements that supported the introduction of the various technologies described in Section 2.2. Using a statistical modeling approach, we also found that a positive and significant relationship exist between the onset of technology-forcing regulations and the level of innovation.[5]

Industry experts also confirmed our empirical finding that government regulations had influenced innovation in automobile emissions control technologies. One expert who had 38 years of experience in automobile emissions control technology claimed that "emission regulation is the basis of many innovations that happened in automobiles." Another industry expert claimed that "it [1970CAAA] really resulted in a quick shift in the focus of the automotive industry and again creating the emission control industry that would not have taken place if standards were not adopted."

4.2. *Sources and the locus of innovation*

4.2.1. *Sources of innovation: the overall picture*

Automakers and suppliers were the major players in the development of automobile emissions control technologies, accounting for more than 93% of patents and 73% of technical papers. The roles of other players on relevant R&D activities, including universities, government agencies, and private research institutes, were notably lower as far as patenting activities were concerned (Figs. 4 and 5).[6] In particular, university's share of patents in automobile emissions control technologies was found to be only 0.5% of the total number of successfully applied patents. Although universities were relatively more active in publishing technical papers (approximately 12%), the number of published papers by universities was less than 30% of the number of papers automakers and suppliers published. Impact of science as the sources of knowledge for patenting activities was also low: non-patent citations such as journal articles including SAE publications only accounted for 5.1% of total citations for patents.

Table 2 shows automobile emission control patents by country of origin. The US and Japan dominate, accounting for 80.1% of total patenting. Germany accounts for 13.1%, and other countries together account for 6.8%.[7] Fig. 6 shows yearly patenting of automobile emission control technologies by country of origin (US, Japan, Germany, and other countries). Japanese patenting activities lagged behind those by US institutions in the early 1970s, but have outpaced patenting by US institutions since the mid-1970s. German patenting activity was comparatively weaker than those by the US and Japanese institutions throughout the period of study.[8]

Fig. 7 shows the number of patents plotted against the number of SAE technical paper publications by the major players in automobile emissions control technologies. Top patenting firms were also heavily involved in technical paper publication activities. However, Japanese automakers and component suppliers, while being some of the leading patenting firms, had a much lower comparative level of publications. A potential reason may be the existence of a vibrant community of researchers in Japan in these areas, which would be sufficient for the exchange of research ideas, but that cannot leverage in terms of intellectual property protection in the US.

Table 3 shows the top 15 institutions that received high number of citations or references from automobile emissions control patents and publications. Major patenting and publication institutions also received a high number of citations and references.[9]

We also examined non-patent citations, such as journal publications like those of SAE, in our patent database to estimate the impact of sciences, which serve as sources of knowledge, on patents. This study showed that non-patent citations account for approximately 5.1% of total citations in the patent database. SAE publications alone accounted for approximately 1.6% of patent citations. Similarly, for SAE publications database, patents accounts for only 1.3% of total references.

[5] Based on the marginal effect analysis, this study estimated that increases in stringencies resulting from the enactment of CAAA1970 and CAAA1990 led to a 181% and a 15% increase in patenting activities, respectively Both regression coefficients are significant at $p<0.001$ level.

[6] Our interviews with experts in the field did mention that they (firms) worked with other research institutes including universities through funding and contract research. Yet, it is highly plausible that auto firms had agreements to control patents. Thus, actual contribution by university as well as other research

(*footnote continued*)
institutes could be higher than what was examined through analysis of patent assignees.

[7] European companies in total account for approximately 19.4% of patenting in auto emission control technology.

[8] Relatively weaker patenting by European countries can be explained by a number of factors. First, the discussion of stricter emission standards did not start until the beginning of the 1980s in Europe. More importantly, there were opposing interests among different European countries over different technological choices (three-way catalysts versus lean-burn engines) for lowering auto emissions, and the agreement on adopting stricter auto emission regulation, which required implementation of catalytic converter, was only established by the end of 1987 even though three-way catalysts had been implemented in the US and Japan since 1981 (Nill and Tiessen, 2005). Unlike European countries, Japan quickly adopted the most stringent US emission control regulatory standards in the 1970s and forced its domestic automakers to develop advanced emission control technology necessary to satisfy regulatory standards. Although Honda was involved in developing CVCC engine to meet stringent regulatory standards, Japanese automakers realized that CVCC engine could not be a viable solution and concentrated on developing catalytic converters (Nill and Tiessen, 2005; Zhu et al., 2006).

[9] The impact of self-citations on the citation ranking is deemed low since self-citations account for approximately 10% of overall citations.

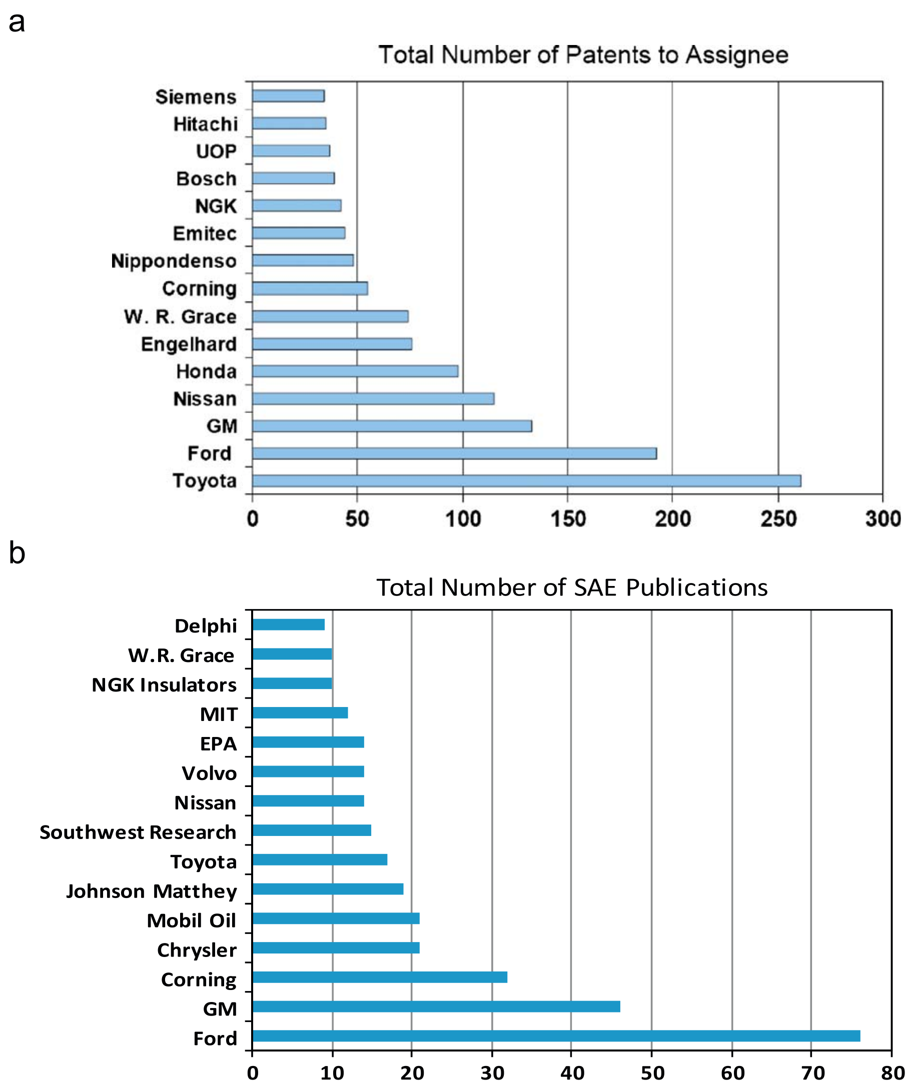


Fig. 4. Top patenting (a) and SAE paper publishing institutions (b), 1970–1998.

4.2.2. Locus of innovation and technology evolution

Looking at the locus of innovation throughout the entire period of our analysis, we found some important changes over time. Before the introduction of the first-generation catalytic converter in 1975, diversifying entrants that specialized in supplying catalyst materials – including Engelhard, Johnson Matthey, and Corning – were leading the innovation rather than the incumbent automakers. Consequently, the mean number of successfully applied patents by catalyst suppliers is found to be significantly higher than that by incumbent automakers before 1975 (Fig. 8).

After the introduction of the first-generation catalytic converters in 1975, patenting by automakers and suppliers of auto electronics outnumbered those by catalyst suppliers (Fig. 8). This finding supports the idea that both automakers and electronics suppliers were strengthening their positions as main innovators. Auto electronics became a critical part of emissions control technologies because auto electronics enabled the simultaneous reduction of all three major pollutants (HC, CO, and NO_x) through sophisticated control of air-to-fuel ratio. Moreover, the advanced electronic onboard diagnostic system, which monitored and controlled the functioning of emission-related components in automobiles, helped automakers satisfy the more stringent pollutant reduction requirements mandated by the 1990CAAA.

In particular, the results show that automakers were the principal locus of innovation after the introduction of the first-generation catalytic converters in 1975 and have remained as such since then. Total patent share by automakers increased over time. Percentage of patents successfully applied by automakers increased from 40.55% in the 1970s before the phase-in of the 90% emissions reduction requirements in 1981. Their share increased to 45.22% during the 1980s prior to the phase-in of CAAA1990. With the phase-in of the CAAA1990, the share of automakers' patents further increased to 49.93% in the 1990s. A further exploration of the nature of the patents shows that automakers pursued both in-house R&D activities in components in addition to their existing areas of expertise in architectural innovation. This finding implies that automakers were active as "system integrators" in product development. System integrators are the firms that integrate and coordinate the internally developed and externally produced works of suppliers (Robertson and Langlois, 1995; Brusoni et al., 2001). This notion on the division of innovative labor across automakers and suppliers, especially in terms of research in architectural and component technologies, is explored in greater detail in the next section.

4.3. Knowledge management and task uncertainty

It is clear that the industry was unable to achieve the new emission standards with existing technologies (Doyle, 2000;

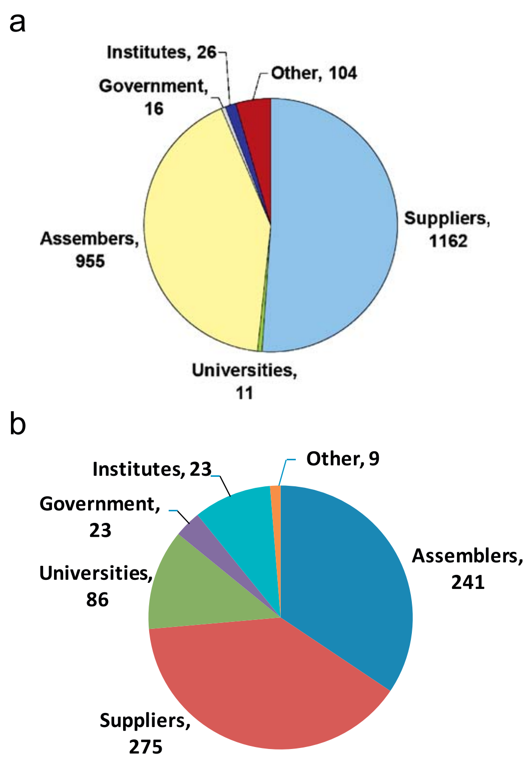


Fig. 5. Contributors to innovation: share of patents (a) and SAE paper publications (b) by different types of institutions, 1970–1998.

Table 2
Proportion of USTPO patents by inventor nation of origin.

Inventor nation of origin	Proportion of patents (%)
United States	42.0
Japan	38.1
Germany	13.1
Others	6.8

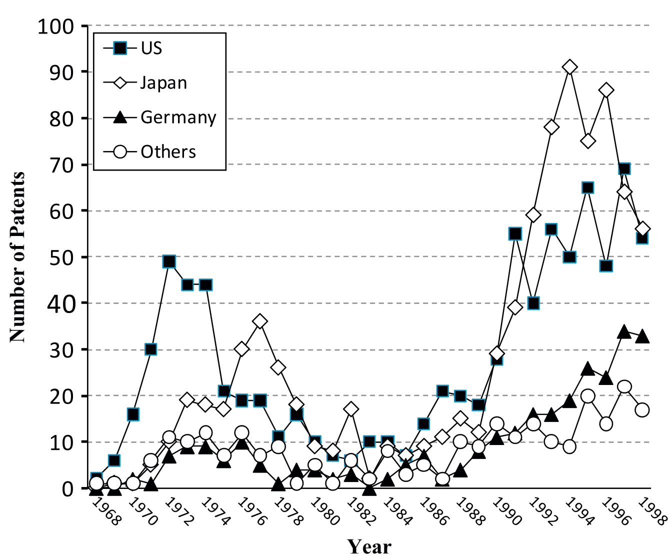


Fig. 6. Patenting in automobile emission control technologies by country of origin.

Mondt, 2000). If one considers uncertainty as the lack of information necessary to perform a task (Galbraith, 1974; Premkumar et al., 2005) then, with each major regulatory target and timeline, the industry faced a compressed period of

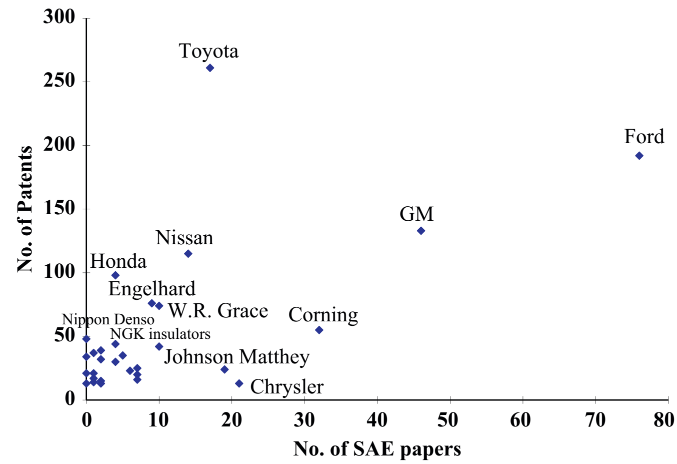


Fig. 7. Top contributors to automobile emissions control technologies:patents vs. SAE technical articles, 1970–1998.

heightened technological uncertainty which was only resolved when a set novel solutions finally made it to the market. While the government dictates some of the variables and targets, which may reduce some of the "Knightian uncertainty" (Knight, 1921), the industry does feels less control over the probability of the outcomes of events (Knight, 1921; Garner, 1962). First, technological solutions in satisfying regulatory demands do not yet, exist; therefore, firms are left to determine which technological path to purse to develop new technology capable in satisfying regulatory standards. Second, probability of success for chosen technological path is unknown; and lastly, market reaction to new technology is not known.

Thus, we wanted to understand how automakers and component suppliers structured their R&D under these heightened uncertainties created by the regulations and over the course of technology evolution.[10] Moreover, prior literature on supply-chain relations in product development has also clearly shown that firms coordinate and communicate more with their suppliers when task uncertainty exists (Wasti and Liker, 1999; Sobrero and Roberts, 2001; Petersen et al., 2003). Brusoni et al. (2001, 2005) also suggested the need for systems integration capability that helps firms maintain a loosely coupled network of suppliers, especially in the development of multi-technology products. Consequently, we expect that the task uncertainties implicit under regulatory pressures would induce the automakers and suppliers involved in inter-firm product development to expand their R&Ds in the directions that would help them better coordinate problem-solving activities with the firms they collaborate with. For automakers, deeper component knowledge would help them better understand and coordinate with the suppliers. Similarly, for suppliers, a higher level of architectural knowledge of the product would improve their capability to solve problems jointly with automakers. Using survey data obtained from Japanese automakers and suppliers, Takeishi (2002) also showed that those automakers that engaged in inter-firm product development attained a higher level of component knowledge when the project involved new technologies.

To examine this issue further, we classified patents into architectural and component-specific innovation categories. We

[10] Technology-forcing regulations create high uncertainty for the following reasons. First, technological solutions in satisfying regulatory demands do not exist yet. Therefore, firms are left to determine which technological path to purse to develop new technology capable of satisfying regulatory standards. Second, the probability of success for chosen technological path is unknown; and lastly, market reaction to new technology is not known.

Table 3
Top 30 institutions as the sources of innovation for patenting and SAE paper publications.

Sources of innovation for patenting activities	Number	Sources of innovation for SAE publications	Number
Toyota Motor Corporation	1483	Ford Motor Company	882
Ford Motor Company	851	General Motors	754
General Motors	787	Corning	313
Engelhard Corporation	707	Environmental Protection Agency	310
Nissan Motor Company	688	Massachusetts Institute of Technology	233
Universal Oil Products Company	591	Toyota Motor Corporation	203
W.R. Grace & Co.	475	Chrysler Corporation	187
Robert Bosch Corporation	471	Johnson Matthey	160
Corning	447	Mobil Oil Corp	160
Honda Motor Company	430	Southwest Research Institute	140
Nippondenso Co., Ltd.	362	Engelhard Corporation	122
3M	270	California Air Resources Board	114
NGK Insulators Ltd.	250	Volkswagen AG	113
Du Pont	219	EMITEC GmbH	104
Hitachi Ltd.	197	W.R. Grace and Co.	95

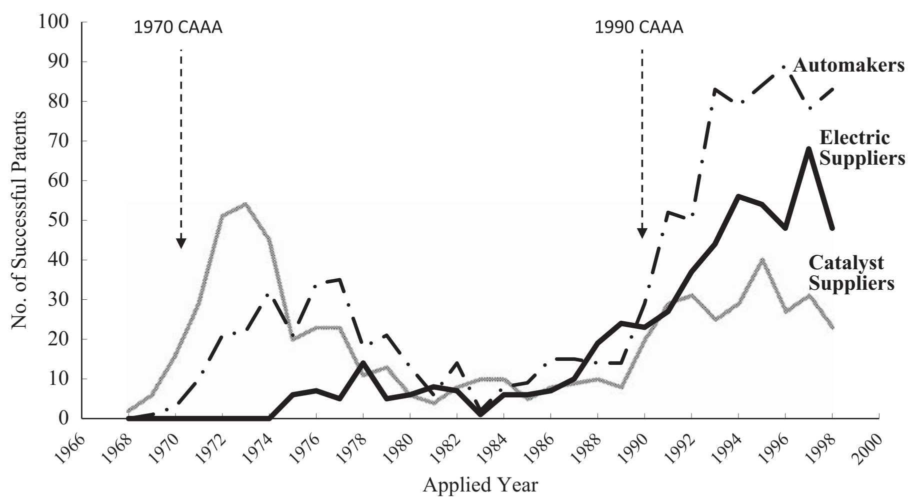
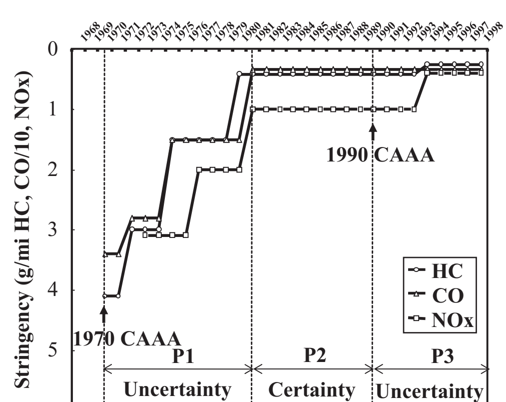


Fig. 8. Comparison of patenting trends by automakers, auto electronics, and catalyst suppliers.



Types of Innovation		P1	P2	P3
Architectural	Automakers	52.2%	87.0%	61.0%
	Suppliers	47.8%	13.0%	39.0%
Component	Automakers	28.6%	26.4%	39.4%
	Suppliers	71.4%	73.6%	60.6%

Fig. 9. Strategic partitioning of knowledge: changes in the proportion of architectural and component knowledge possessed by automakers and suppliers, 1970–1998.

used the generic definition of component and architectural innovation extant in the literature to parse patents into architectural or component categories (Henderson and Clark, 1990). For example, innovations in the catalyst technology category, such as advanced catalysts and catalyst support materials were coded as component innovation. Innovations like air-to-fuel ratio control or electronic emissions recirculation technologies were coded as architectural innovation since these technologies embody knowledge on the ways by which components are linked together (Henderson and Clark, 1990). After classification, we defined periods of uncertainty as those implicit with the regulatory performance stringencies imposed under technology-forcing regulations in the auto industry from 1970 to 1998. Period outside these was considered times of certainty. More specifically, the periods from 1970 to 1981 (P1) and 1990 to 1998 (P3) were defined as periods of uncertainty because of the presence of regulatory pressures during the time (1970CAAA,1990CAAA, and NLEV). The period between 1982 and 1989 (P2), when there was absence of regulatory pressure, was defined as period of certainty.

Fig. 9 also shows the shares of the architectural and component innovations possessed by automakers and component suppliers for the three periods (P1, P2, and P3) between 1970 and 1998. The results show that automakers and suppliers dominated architectural and component innovation, respectively, throughout the entire periods. Moreover, as

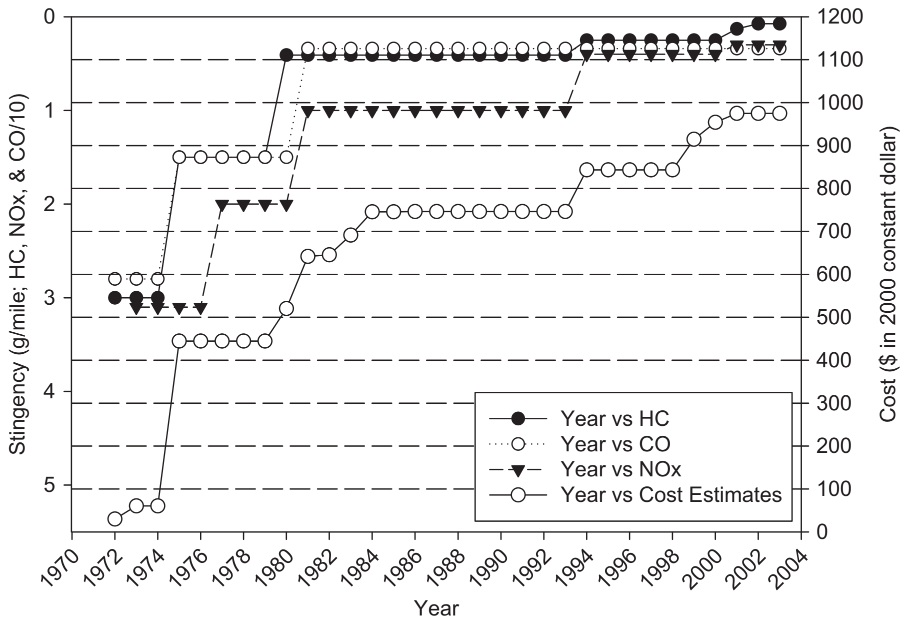


Fig. 10. Estimated costs of automobile emissions control devices, 1972–2003.

expected, component innovations by automakers and architectural innovations by component suppliers increased with the imposition of more stringent regulatory standards during the 1970s and 1990s (Fig. 8).[11] Automakers acquired 28.4% and 39.4% share of component innovation during periods of uncertainty (P1 and P3) compared with the 26.4% share of component innovation during the period of certainty (P2). Similarly, suppliers' shares of architectural innovation were at 47.8% and 39% during periods of uncertainty compared with the 13% during the period of certainty. These findings confirmed our expectation that suppliers' and automakers' propensity for architectural and component innovation, respectively, would increase amid task uncertainties.

4.4. Learning by doing

Fig. 10 shows the average cost of emissions control system per vehicle from 1973 to 2003 adjusted to a constant 2000 dollar. Cost data used for Fig. 10 came from number of different sources that include the EPA (1990) and the California Air Resource Board (CARB, 1996). The EPA's (1990) cost estimates[12] included evaporative emissions canisters from MY 1972, high altitude emissions controls from MY 1984, catalytic converter beginning MY 1975, exhaust gas recirculation units for MY 1973–1974, and air pump units for MY 1970–1974 (EPA, 1990; McConnell et al., 1995).[13]

Notable increases in device costs occurred in 1975 as the auto industry introduced oxidation catalysts to satisfy intermediate emission standards. There is also a steep increase in cost estimates from 1980 until 1984. This increase seems to capture heightened costs in introducing more advanced three-way catalysts with electronic loop control. The EPA (1990) study reveals that to achieve a 90% of tailpipe emissions reductions from pre-1970 emission levels would cost an additional $746.3 per vehicle. Continuing work by the EPA shows that the cost of emissions control system further increased in 1994 owing to the phase-in of Tier I standards (Anderson and Sherwood, 2002). Tier I standards caused an additional cost of approximately $97.2 (Anderson and Sherwood, 2002). The cost of an emissions control system increased anew in 1999 owning to the adoption of the National Low Emission Vehicle (NLEV) program. The NLEV program was intended to introduce nationwide a more stringent California LEV program, which was adopted in 11 northeastern states. Under the NLEV program, the required emissions stringencies gradually increased from Tier I to the more stringent Low Emission Vehicle (LEV) standards, and all vehicles were mandated to conform to the LEV standard by 2001.

Based on detailed examinations of incremental component costs owing to TLEV and LEV, CARB (1996) reported that the estimated incremental costs of emissions control systems for TLEV and LEV standards in comparison to Tier I standard are $83.3 and $132.0, respectively. The overall cost of an emissions control system owing to the NLEV program increased from $843.3 in 1998 to $975.0 in 2001, and remained at $975.0 until the phase-in of the Tier II standard in 2004.

However, the cost analysis does not consider the non-pecuniary aspects of costs such as drivability and cold-start performance. Bresnahan and Yao (1985) claimed that when one takes into account the non-pecuniary elements of costs, the compliance costs over time may be reduced significantly. Their claim is based on observations that quality improvements, such as in drivability, realized by technological advances in emissions controls (for example, closed-loop control, TWC, and fuel injection) offset the impact that increasing stringencies have on costs in most time periods.

[11] We have developed a statistical model based on probit estimation approach using component innovation as the dependent variable. Results of statistical analysis largely confirmed results from analyzing the share of architectural and component innovations possessed by automakers and component suppliers.

[12] EPA (1990)'s study reported that the costs of device remains 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.

[13] 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). McConnell et a study incorporated a number of different sources in providing cost estimates such as *the Survey of Current Business* by the Bureau of Economic Analysis (BEA) and studies by White (1982), Crandall et al. (1996) and Wang et al. (1993).

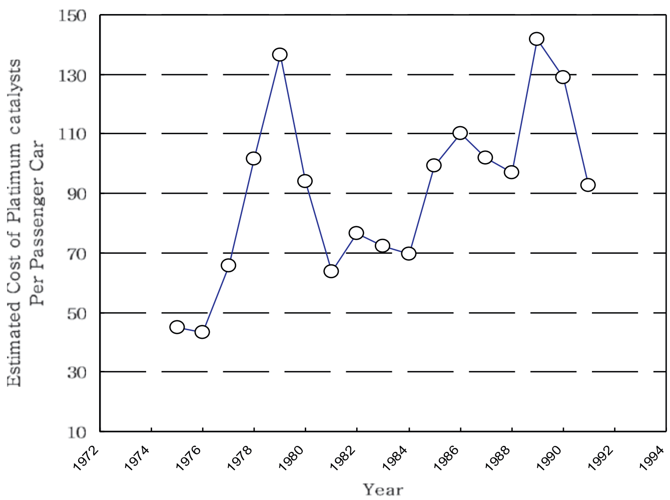


Fig. 11. Estimated costs of installed precious metal catalysts per automobile ($ in 2000 constant dollars).

4.4.1. *Learning in the 1980s*

The cost data shown in Fig. 10 shows no apparent "learning" during the 1980s. A learning effect implies a fall in per-unit costs with increases in cumulative output. One would expect automakers in the 1980s to learn ways to reduce their costs since they faced no stringency increases from 1981 until 1994. However, this did not seem to have happened.

Potential cost reductions in emissions control devices during the 1980s owing to learning by doing could possibly have been nullified by the increases in the costs of precious metal catalysts during this period. Automotive applications account for a major portion of overall precious metal consumptions. The use of rhodium (Rh) and platinum (Pt) precious metals for automotive applications made up approximately 87% and 40% of the overall consumption, respectively (Degobert, 1995). Fig. 11 shows the estimated costs of platinum metals used per passenger car. The estimation was based on typical compositions of platinum metals per passenger car reported by Heck and Farrauto (2002) and Degobert (1995). Heck and Farrauto (2002) and Degobert (1995) reported that typical compositions for oxidation catalysts are Pt and Pd in a 2.5:1 or 5:1 ratio; and Pt and Rh in a 5:1 ratio (or Pt/Pd/Rh ratio of 10/4/1) for three-way catalysts ranging from 0.05 to 0.1 troy oz/car.[14] According to the cost estimations, cost of precious catalyst materials per car ranges from $72 in 1984 to $142 in 1990. Since, the cost of emission control devices remained fixed at $746 from 1984 (Fig. 10), estimated costs of precious catalysts per car represent about 9.5–18.9% of overall costs of emission control devises. Table 4 shows the breakdown of costs for a three-way catalytic converter (Degobert, 1995). According to Table 4, precious metals account for approximately 23.3% of overall cost for catalytic converters. Since McConnell et al.'s (1995) study incorporated other emission control devices, such as air pumps and EGR not considered in Degobert's (1995) study, the estimated range 9.5–18.9% in this study seems reasonable (Fig. 12).

Fig. 11 also shows that the estimated costs of installed precious metal catalysts per vehicle increased throughout the 1980s. Thus, the finding that the overall costs of emission control devices did not change after 1984 support the idea that the potential reductions in costs due to learning could possibly have been nullified by the increases in the costs of precious metal catalysts. Industry experts have also supported the view that no apparent reductions in the costs of automobile emissions control devices during the 1980s could be attributed to the costs of precious metals. They claimed that the supply of precious metal was rather fixed, and this may have caused the costs per-unit catalyst to go up as sales volume increased.[15]

To have a complementary perspective on the issue, we looked at the evolution of cost for the non-catalyst components of automobile emissions control devices from 1984 to 1990.[16] These should not have been affected by the fluctuations in the price of precious metals. Fig. 9 shows a significant learning associated with the non-catalyst components of automobile emissions control devices. We estimated that reductions in the costs of non-catalyst components due to learning took place with a progress ratio of 0.93 between 1984 and 1990. This is comparable with the empirical estimates of the progress ratios of other industries (Dutton and Thomas, 1984; Argote, 1999). However, this progress ratio can only be understood as a rough estimate, more on an indication, rather than a precise estimate. In fact, the estimation is based on the important assumption that the increasing costs of precious metal catalysts have driven the costs of overall emissions control devices, rather than observed

Table 4
Cost breakdown (%) of three-way catalytic converter components.
Source: Degobert (1995).

Converter component	Proportion of costs (%)
Catalyst support	13.3
Impregnation costs	36.7
Precious metals	23.3
Casing	26.7
Total	100.0

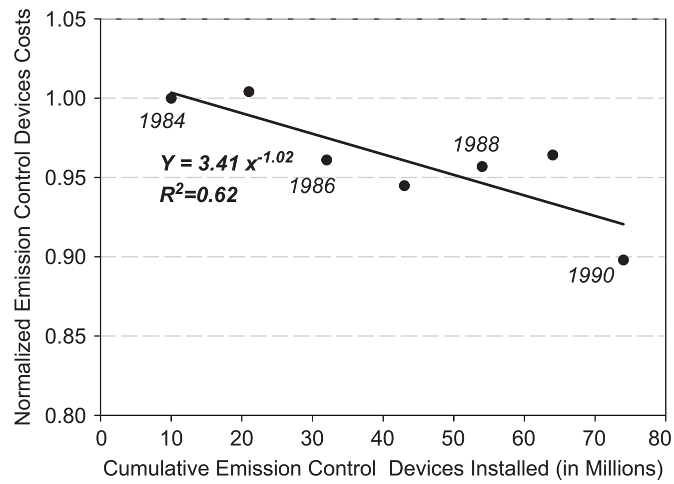


Fig. 12. Normalized experience curve for the non-catalyst components of emissions control device costs.

[14] We used historic price data for platinum metals reported by KITCO in our cost estimation. Unfortunately, automobile manufacturers did not share such cost data, so average price data had to be used instead. Historical data for precious metals were obtained from kitco.com; www.kitco.com.

[15] Although, expert expressed their support for our analysis, they were not able to provide any historical costs data for precious metals.

[16] We plotted an experience curve until 1990 because the Amendment to the Clean Air Act was enacted in 1990. Enactment of more stringent regulation could have significant influences on firms' existing production practices and learning as firms were required to install more advanced equipments to automobiles.

reduction in the costs of emissions control devices. Moreover, it is based on a very limited number of points.[17]

5. Discussion and conclusions

This study examined the innovation processes involved in the development of automobile emissions control technologies from 1970 to 1998. Analyses have shown that the innovation in automobile emissions control technologies was driven by technology-forcing regulations. The technology-forcing regulations were found to be successful in forcing not only the introduction but also the development of advanced emissions control systems.

Automakers and component suppliers were the dominant contributors of innovation in automobile emissions control technologies, holding more than 90% of the total patents awarded in this domain. The major innovating suppliers were typically diversifying suppliers originally engaged in the production of specialty chemicals but later on engaged as well in the production of emissions control catalysts. Contributions from other institutions such as universities, public or private research institutions, and government agencies were surprisingly minimal. Altogether, they account for less than 3% of the overall patenting activities. Their contributions to the total technical paper publications is higher at approximately 25%, but automakers and component suppliers remained dominant in both the patenting and publication of technical paper.

Subsystem-level analysis of technological change showed that the focus of innovation activities gradually shifted from catalysts to electronic feedback system during the life cycle of these technologies. Automobile emissions control technology consisted almost entirely of oxidation catalysts when these were first introduced in 1975. Although catalysts remained as core components of emissions control technology, emphasis on strengthening emissions reduction capability led to a shift in the focus of innovation from catalyst materials to auto electronics that control and monitor the operations of main emissions control devices. Analysis further showed that automakers' role as the innovators were further reinforced over time. Automakers emerged as the locus of innovation since the late 1970s, although there were waves of technological shifts in component subsystems. This finding strongly supports the idea that automakers are not merely assembling subcomponents into a system, but they are system integrators that coordinate "change(s) across a large number of technological fields that may well be developed by an external source." (Brusoni et al., 2001, p. 614). The role of automakers as systems integrators implies that they possessed the knowledge not only in systems architecture but also in components. Periodic introduction of new architecture and the need for maintenance of such capability requires firms to be knowledgeable in all aspects of the system (Brusoni et al., 2001; Prencipe, 2002). Detailed patenting analysis confirmed that automakers did indeed invest significantly in component knowledge, such as in catalyst compositions.

Cost changes in emissions control devices closely followed changes in regulation stringency. Imposition of stricter regulations in the 1970s led to simultaneous increases in the costs of emissions control devices, and stable stringencies in the 1980s caused no changes in the costs of devices during this period. Interestingly, the study found no apparent ''learning' during the 1980s despite the stability of regulatory standards. However, a rather sharp increase in the prices of precious metals during the 1980s may have countered any gains from learning. In fact, a refined analysis suggests that there was ''learning'' associated with the non-catalyst components of emissions control devices.

5.1. Policy and managerial implications

5.1.1. Command-and-control type regulation

The findings that the imposition of more stringent regulations induced innovations provide an indirect empirical support to the ''narrow'' version of the Porter hypothesis, which states that certain types of environmental regulation (in this case, technology-forcing regulations) stimulate innovation (Jaffe and Palmer, 1997). Yet, many academics have claimed that command-and-control (CAC)-type regulatory policies can be very counterproductive (e.g., Palmer et al., 1995; Greenstone, 2002; Jaffe, 2002). They claim that by imposing uniform standards on firms, regulatory compliance can be very counterproductive. Moreover, stringent regulatory standards could run the risk of being unattainable because it is impossible to know prior to the regulation how much improvement the regulation can achieve.

This study showed that the CAC-type technology-forcing regulation was successful in driving innovative responses from the industry. The history of automobile emissions control regulations reveals that automakers were initially reluctant to adopt an add-in type of catalytic converters and instead pursued the option of modifying existing engine components in their attempts to reduce tailpipe emissions. However, the stringency of emissions control regulations, especially the requirement that NO_x be controlled at less than 1.0 gram per mile, forced automakers to give up on their approach in the mid-1970s of reducing emissions control using engine modifications. This technology-forcing regulation certainly forced the industry to develop different approaches to reducing emissions, and it is very reasonable to say that the industry would *not* have adopted catalytic converters had the regulation not been implemented. Moreover, it is clear that the industry responded to the regulation by increasing the level of innovative effort, as measured by the amount of patents, rather than exploiting technologies that were already available but not necessarily commercialized.

Although this study lacks a detailed analysis of the costs and benefits of the arguments resulting from automobile emissions control, it seems reasonable to assert that government intervention in the form of technology-forcing regulations has influential power as the driver of technological innovation and adoption. 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 more than 30 years of regulatory actions, all new cars today are indeed equipped with emissions control devices capable of reducing CO, HC, and NO_x by more than 95% (Bertelsen, 2001). Nevertheless, it is important to recognize that we do not explicitly consider a comprehensive discussion on environmental legislation, which goes beyond the scope of this article. Yet, we believe that our results focusing on "emission control legislation" do have important implications to "environmental legislation," as it considers its innovative dimension.

5.1.2. Internal structures of regulations and technological change

The finding that the auto industry increased the intensity of its innovation from the late 1980s, *prior to* the actual enactment of the 1990CAAA that imposed more stringent emissions reduction requirements, provides evidence to the tendency of a regulated industry to innovate *in anticipation of* new and formal regulatory standards. One interesting implication of this finding is that the *uncertainties* implicit in the anticipation of regulation may themselves have driven the

[17] We acknowledge that this study did not explore potential alternative sources of cost reductions such as economies of scale. Future study that incorporates more in-depth analyses on alternative sources of cost reductions could provide fuller understanding on how learning took place in the development of auto emissions control technologies.

innovation.[18] Nevertheless, Taylor et al. (2005) claimed that the "informed traditional" environmental policies combining demand-pull with technology-push approaches would be a better alternative for inducing innovation. The expectation is that with the "informed traditional" approach, the rate of technological innovation and learning would be faster, and the time to reach the lowest cost would be shorter. Porter and van der Linde (1995) also shared a similar view. They believed that the coordination of environmental regulations can have a significant impact on innovation, and "the regulatory process should leave as little room as possible for uncertainty at every stage (Porter and van der Linde, 1995, p. 110)." Literature in regulatory economics showed that one of the key drawbacks in the implementation of technology-forcing regulation is the agency's credibility in enforcing the standards (e.g., Kleit, 1992; Gerard and Lave, 2005). Firms may lower costs or not even invest in potentially new technological approaches if they know that there is low probability for a new regulation to be enforced. Moreover, firms may try to influence regulatory agencies strategically by taking advantage of an information asymmetry that exists between the regulatory agency and firms (Marino, 1998).

This implies that vast technical knowledge and technology assessment skills are necessary for regulatory agencies to be capable of setting an appropriate level of stringencies (or uncertainty) in forcing innovation. Employing *intermediary organizations* that inform the status of technical change to a regulatory agency would be helpful. The agency may accept feedback and use the information to set future regulations.

5.1.3. Technological advances and the sources of innovation

5.1.3.1. Science, University, and Technological Change. There is a long tradition of studies looking at the linkage between industry innovation (technological advancements in industry) and science, many of them looking at patents (e.g., Nelson, 1986; Jaffe, 1989; Klevorick et al., 1995; Narin et al., 1997; Grossman et al., 2001; Zucker et al., 2002; D'Este and Patel, 2007). Firms collaborate with public research institutes, such as universities, for a number of reasons (Czarnitzki et al., 2009). University research can complement firms' R&Ds (Rosenberg and Nelson, 1994; Mowery and Rosenberg, 1998), be used as a guiding principles for R&D directions (Mansfield, 1991) and even be a direct input to firms' R&D activities. Universities participating in collaboration can also benefit from collaboration by overcoming "underfunding" of science (Agrawal and Henderson, 2002). Collaboration may even trigger new research ideas (Rosenberg, 1998). Moreover, studies have shown that ties between public research institutions and industrial R&D expanded over the last three decades (Cohen et al., 2002). University–industry R&D centers have grown more than 60% and there has been eightfold increase in the university technology transfer offices since the 1980s (Cohen et al., 2002).

Despite these findings, it important to note that the contribution of university research to firms varies across industries (Klevorick et al., 1995; Cohen et al., 2002). The impact is typically concentrated in few industries such as in pharmaceuticals, chemical industries, and some areas of electronics (Cohen et al., 2002). Part of the reason is that university faculty members' low incentives for technology transfer in general and applying for patents in particular. Since the implementation of the Bayh-Doly Act in 1980, patenting or licensing of the results of university research has generally increased (Mowery and Ziedonis, 2002; Sampat, 2006). Nonetheless, Agrawal and Hendeson's (2002) study on MIT engineering faculties showed that patents only account for less than 10% of the knowledge transfers from their laboratories. For most faculty members, publishing academic papers is more important than applying for patents (Agrawal and Henderson, 2002). Moreover, as Cohen et al. (2002) note, patenting and licensing are useful mechanism for technology transfer in only a few industries. In other technologies transfer mechanisms such as conferences, consultancies and personal network are important channels for transferring university research.

Therefore, the finding that universities only played a minor role in the development of automobile emissions control technology as revealed by number of patent applications and citations (sources of knowledge) is not totally surprising. These findings may not necessarily imply low contribution in the development of auto emissions control systems as reflected by the percentage of patenting. Firms in the auto industry may have been working collaboratively with public research institutes on auto emissions control technology via funding their research or on contract bases (Cohen et al., 2002); and public research institutes such as universities would have been constrained from freely publishing papers or applying for patents from their contract research.

Another important aspect is the fact that firms were under deep pressure to develop and implement new technological system within a relatively short time frame because of the technology-forcing regulations. This innovation context is rather unique and different from that of prior work looking at industry academic collaboration. Because innovation took place under stringent regulatory pressures, it may not have been possible to establish collaboration R&D with universities, which typically operate with long cycles. In fact, this is an important novel observation adding to the literature on these topics; but also one that merits further investigation. Future research should examine in detail R&D ties and research outputs between public research institutes and industrial innovation under a rapid technological shift to enhance our understanding on the potential influence of scientific research on the advancement of industrial innovation as well as on technology evolution under these particular contexts.

5.1.3.2. Incumbent as the locus of innovation. The finding that incumbent automakers remained strong as the locus of innovation since the mid-1970s provides an interesting insight into understanding incumbent firms' competitiveness during the rapid technological changes. Automakers remained as the locus of innovation despite the emergence of competence-destroying technological discontinuities in catalysts and advanced electronics in the 1970s and the 1990s. This finding may imply that automakers' in-house R&D capabilities in the subsystem (or components) could be a crucial factor for their continued success as the locus of innovation especially involving the complex system that consists of multiple subsystems. Automakers' need for system integration must have forced them to invest their technical capabilities not only in system architecture but also in components (Grandstrand et al., 1997; Brusoni, 2005). Therefore, future research may need to examine in detail the cross-sectional composition of systems integrators' technical expansion and how their expansion relates to the emergence of subsystem-level technological changes and dominant designs.

6. Conclusion and future research

Analysis finds that properly designed CAC- type *technology-forcing* regulations can provide incentives for R&D. This is an important finding for the current debates on the potential

[18] By uncertainties, we mean "technical uncertainties" rather than "regulatory uncertainties." Under technology-forcing regulations, firms know that they could not meet regulatory standards with their existing capabilities and have to find new technological approaches to satisfy stringent regulatory standards. Uncertainties regarding technological solutions would have induced firms to innovate to successfully satisfy regulatory demands and to get ahead of competitors in the market place.

enactment of ever more stringent environment regulations for inducing technological innovation. Under stringent domestic US regulations, US auto industry became highly innovative. Moreover, European countries were significantly behind US and Japan in implementing stringent regulatory mandates for controlling tailpipe pollutants from automobiles (Nill and Tiessen, 2005). Findings of this study suggests that stringent technology-forcing policies can be used to strengthen the innovation capacity of domestic firms in the current fiercely competitiveness market for new products. Future research that incorporates international trade dimensions with regulatory pressures and patenting activities of regulated firms could solidify the notion that there is a relationship between stringent regulatory pressures and competitiveness of regulated firms. Furthermore, the study also shows that automakers and suppliers are the lead innovators of auto emission control technologies. This finding suggests that technological innovation in the industry, and consequently the ability to respond to technology-forcing regulation, depends significantly on the competence of component suppliers. As a result, evaluating innovative capabilities of supplier networks would be crucial for a successful implementation of policies designed to force innovation in the industry.

While this research provided interesting conclusions, it is important to note some limitations. In particular, this study did not explore the changing dynamics in technical communities under a regulatory environment. Technological evolution inevitably involves the formation and evolution of key technical communities along the course of technical change (Koka et al., 2006). Consequently, understanding the structural relationships and changes in the key players, and their linkages with exogenous environmental events should provide a clearer picture of the forces that drive technological evolution and the success of government regulations in stimulating innovation (Rosenkopf and Tushman, 1994).

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