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**Inter-Firm Innovation under Uncertainty:  
Empirical Evidence for Strategic Knowledge-Partitioning**

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# **Inter-Firm Innovation under Uncertainty: Empirical Evidence for Strategic Knowledge-Partitioning**

## **ABSTRACT**

This paper describes how firms' propensity to carry out component (or architectural) innovation is influenced by the degree of task uncertainty during inter-firm product development. Using successfully applied patents in automobile emission control technologies from 1970 to 1998; this research shows that assemblers' and suppliers' propensity to expand their knowledge base in component and architectural knowledge increased under higher task uncertainty respectively. This finding provides large scale empirical justification for theoretical claim that firms' should know more than what they make (Brusoni, Prencipe et al, 2001) and an overlap in knowledge domain exists between an assembler and a supplier for projects involving new technologies (Takeishi 2002). Importantly, this study also shows how architectural innovation prevails in the early phase of technological changes, while component innovation dominates the later stages. Furthermore, unlike what could be anticipated, total assemblers' effort to build up in-house component innovation increases continuously over time, suggesting that product life cycle effects may dominate over that of task uncertainties. This paper strongly suggests that effective knowledge management for both architectural and component knowledge is a key factor influencing firms' competitiveness in the inter-firm product developments.

Key words: uncertainty, inter-firm innovation, knowledge management, product development

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## INTRODUCTION

Inter-firm relations have attracted growing attention, especially since the 1980s (Sobrero and Schrader 1998; Sobrero and Roberts 2001; Bossink 2002). Competitive business environments are increasingly requiring that firms leverage their internal resources in their core competences and strategically use inter-organizational relationships to complement these competences (Sobrero and Roberts 2002). Strategic collaborations such as R&D joint ventures (Pisano 1990; Greenlee 2005), consortia (Tripsas, Schrader et al. 1995) and alliances (Hamel 1991; Emden, Calantone et al. 2006; Geyskens, Steenkamp et al. 2006) have the potential to reduce fixed costs, increase flexibility and allow learning from other organizations, thus enhancing firms' innovation capabilities (Dyer 1997; Brusoni, Prencipe et al. 2001; Sobrero and Roberts 2001). Portfolio approach where firms engage in variety of inter-organizational collaborative arrangements was also found to be effective in innovative performance (Faems, Looy et al. 2005). Studies of supplier-assembler relationships in product development report that collaborative design work beyond the strict outsourcing decision has become an important dimension for many firms (Takeishi 2002; Kotabe, Martin et al. 2003; MacDuffie and Helper 2005). In traditional approaches, the role of suppliers is limited to make sure that their provisions meet technical manufacturing specifications in the context of a fully specified client outsourcing decision. But nowadays, suppliers in most industries have expanded their role, becoming active participants in the development of ever more complex and sophisticated products (Lakemond, Berggren et al. 2006). At the

same time, these products gain greater interdependency with the final object that their client is producing (Dyer and Nobeoka 2000;).

This trend is making the complex process of effective inter-firm management a growing challenge. Transaction costs economics (Williamson 1979) has long demonstrated that, despite all the potential advantages from inter-firm collaborations, firms need to be aware of potential adverse outcomes due to the opportunistic behavior of involved parties. When knowledge-intensive R&D processes between firms are involved, potential problems with appropriating benefits from investment have an important influence in the decisions regarding inter-firm governance structures (Pisano 1990; Wolter and Veloso 2006). Outsourcing in product development is no exception. Although such outsourcing has become an important strategy for many firms (Liker, Kamath et al. 1996; Takeishi 2001), it poses potential risks (Takeishi 2002). Firms depending heavily on suppliers for engineering capability may lose negotiation power (Clark and Fujimoto 1991; Takeishi 2002). Moreover, critical engineering design and information may leak to competitors through suppliers (MacDuffie and Helper 2005).

To counter these potential hazards, Fine and Whitney (1998) argue that firms (assemblers) ought to rely on their suppliers for tasks, but not for critical knowledge. By doing this, firms could live with outsourcing without substantial risks. Fine and Whitney's core argument is based on their observation that there are two categories of dependency: dependency for capacity and dependency for knowledge. Dependency for capacity suggests that an assembler relies on suppliers merely for their manufacturing capacity whereas the dependency for knowledge implies that an assembler does not

possess the necessary knowledge to develop and produce the focal product, thus necessarily requiring suppliers' expertise (Fine and Whitney 1998). Risks involved in outsourcing would be greater in case when an assembler depends on suppliers for their knowledge rather than for their capacity. Based on Fine and Whitney's arguments, Takeishi (2002) introduced a concept of "knowledge partitioning." The idea of knowledge partitioning is different than that of task partitioning. While two firms with a particular division of tasks may still have many similarities in their knowledge spaces, knowledge partitioning implies that different organizations have command over different knowledge spaces and clearly also over different tasks<sup>1</sup>

The notion that a firm can be characterized as an entity with distinct production and knowledge domains has become instituted with the literature on the knowledge-based view of the firm (Grant and Baden-Fuller 1995; Grant 1996; Nickerson and Zenger 2004;). Typically, products do not fully embody the knowledge of a firm, and the knowledge required by a given product may not be fully available from within the firm that supplies it. Empirical evidence from industry studies suggests that firms' knowledge boundaries extend beyond their production boundaries (Patel and Pavitt 1994; Prencipe 1997; Brusoni, Prencipe et al. 2001). However, despite these recent empirical results establishing the difference between task and knowledge boundaries, our understanding of how firms manage and arrange knowledge boundaries and especially how these relate to the characteristics of the task to be performed is still at its infancy. This is especially true in a dynamic sense, in trying to understand how firms manage their knowledge

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<sup>1</sup> Similarly, the concept of knowledge-partitioning differs from that of resource-portioning model proposed by Carroll et al. who used the model to explain prevalence of specialist firms in the more concentrated market environment (Carroll and Hannan 1995; Swaminathan 2001).

boundaries in face of changes in their business environment, task characteristics and strategic directions.

Building on emerging research on knowledge partitioning (Takeishi 2002) and on an information processing view of product development (Galbraith 1974; Adler 1995; Stock and Tatikonda 2004; Song, van der Bij et al. 2005), the present research aims to further our understanding of the link between knowledge partitioning and task characteristics. In particular, this research will examine *how task uncertainty influences firms' strategic knowledge partitioning during inter-firm innovation.*

To analyze these issues, this work investigates patenting behaviors by assemblers and suppliers in automobile industry, looking in particular at how they balance architectural and component-specific knowledge in face of changing uncertainty at the task level. The particular setting chosen is the development automotive emission control technologies over the period from 1970 to 1998, where different levels of stringency in the regulation create variation in uncertainty associated to product development and manufacturing. Automobile emission control systems were chosen for two main reasons. First, automotive emission control technology represents multi-component and multi-technology products involving expertise of assemblers as well as many suppliers. Automotive emission control technology involves subsystems that came from diverse technology disciplines such as electronics and materials which make it an ideal test bed for investigating firms' knowledge partitioning under a context of inter-firm collaboration in product development. Second, automotive emission control technologies were developed under technology-forcing regulatory pressures. Technology forcing regulations

impose standards, which require technological development to meet emission requirements by setting performance levels beyond existing technical capabilities of assemblers (Leone 1999; Jaffe, Newell et al. 2002). Several waves of increasingly stringent regulatory action through technology-forcing acted as a major source of uncertainty for technological development in automotive emission control, forcing firms to develop new technologies within the strict time frames established by the Environmental Protection Agency (EPA). Kemp (1997) notes that, under technology forcing regulation, there is important uncertainty in innovation, especially in cost and availability of technology.

This work makes several contributions to the literature. First, by examining knowledge partitioning practices in a multi-component, multi-technology product, under varying levels of regulatory pressure, this research provides critical insights as to how inter-firm knowledge is managed in highly uncertain innovation environments (Takeishi, 2002; Brusoni and Prencipe 2006) This research also contributes to the literature on product development. Existing work in this area focuses largely on the factors affecting task nature and outcomes (Wasti and Liker 1999; Tatikonda and Rosenthal 2000; Sobrero and Roberts 2002; Hoetker 2004), with little discussion on the factors affecting firms' knowledge partitioning. The proposed research aims at providing both a theoretical approach and empirical examination of the link between task uncertainty and firms' decisions on how to partition knowledge. Third, this work takes a longitudinal perspective on its empirical examination of firms' knowledge partitioning. Thus, this research provides valuable insight not only for how uncertainty influences firms' knowledge partitioning, but also how firms knowledge partitioning change during the



course of inter-firm product developments. Finally, this article also addresses Henderson and Clark's (1990) claims that both architectural and component knowledge are important, but play different roles in the build up of firms' capabilities. In particular, this article will show that the relative and absolute role of each type of innovation depends on the task characteristics and environment, notably the task uncertainty.

The next section of this paper describes the theoretical framework used to derive hypotheses regarding the potential impact of task uncertainty as well as product life cycle on firms' knowledge partitioning. The subsequent section describes the data and a model used to test the hypotheses. Results are then presented, and a general discussion ensues.

## **THEORETICAL FRAMEWORK**

### **Managing Tasks and Knowledge in Outsourcing**

Existing work demonstrates that outsourcing involves risks, even within strong supplier-assembler relations and especially when considering product development (Takeishi 2002). Several risks are involved in design and development outsourcing: first, core design ideas for the system and components may spread to competitors through shared suppliers and clients (MacDuffie and Helper, 2005; Gerwin 2006). Second, procuring components developed by or co-developed with suppliers may erode distinctive features that differentiate the end product of an assembler in the marketplace (Venkatesan 1992; Fine and Whitney 1998) Clients that rely heavily on suppliers' engineering capability may also lose negotiation power with their suppliers and become

vulnerable especially in technological capability by losing engineering expertise (Clark and Fujimoto 1991; Takeishi 2002).

A number of studies have looked at the relations between assembler and supplier at the level of product development, aiming to understand how to deal with risks and find conditions that lead to the best results for both parties (Clark and Fujimoto 1991; Sobrero and Roberts 2002). But their focus has primarily been on task partitioning, looking, for example, at when and how assemblers can benefit from delegating some engineering responsibilities to suppliers (Sobrero and Roberts, 2001). More recent studies in product development, (Wasti and Liker 1999; Sobrero and Roberts 2002; Lakemond, Berggren et al. 2006) address the issue of task coordination, showing that buyers communicate more frequently or with more intensity to better resolve uncertainty. However, hardly any research has addressed the role of knowledge, and existing studies are rather conceptual or descriptive (Fine and Whitney 1998), or based on small samples and perceptual data (Brusoni, Prencipe et al. 2001; Takeishi 2002). Detailed large sample empirical analysis of the linkage between knowledge and competitiveness has yet to be explored.

The need and importance to distinguish knowledge from task in the context of outsourcing decisions was clearly articulated by Fine and Whitney (1998) and more recently by Takeishi (2001; 2002). Fine and Whitney (1998) argue that, to minimize risk, assemblers ought to rely on their suppliers for tasks, but not for critical knowledge. Fine and Whitney's core argument is that firms' competitive advantage constitutes effective knowledge partitioning, which includes identification of "core" strategic component families (Venkatesan 1992), those that normally matter most to the customer or

differentiate their product in the market, and then investment in nurturing internal knowledge associated to them, through in-house R&D, rather than mostly relying on supplier knowledge (Fine and Whitney 1998). Fujimoto (1999) pointed out that: “Effective supplier management firms, such as Toyota, may rely on bundled outsourcing in manufacturing activities, but they may retain technical manufacturing knowledge in-house, partly by taped vertical integration and partly by keeping technical staff in-house for effectively guiding and evaluating the suppliers’ developmental activities.” Brusoni et al. (2001) also found that aircraft engine manufacturers maintained in-house technological capabilities related to outsourced components. They argue that manufacturers’ knowledge boundary should be wider than the production boundary so that manufacturers can “coordinate loosely-coupled networks of suppliers of equipment, components, and specialized knowledge and maintain a capability for system integration.” A recent paper by Takeishi (2001; 2002) further shows that the existence of firm knowledge on areas whose tasks are outsourced to suppliers plays an important role in improving design quality. Takeishi (2001, pp. 419) claimed that “outsourcing does not work effectively without extensive internal effort. The automaker’s early, integrated problem-solving process with the suppliers, frequent face-to-face communication between the automaker and the suppliers, and the level of architectural knowledge for component coordination by the automaker’s engineers, all have a positive effect on component design quality.” In summary, this body of research suggests that risks in outsourcing require knowledge partitioning to be distinguished from task partitioning, with firms needing to retain knowledge domain for critical tasks being outsourced (Fine and Whitney 1998; Takeishi 2001;2002).

These findings provide a critical link to the structural contingency framework (Lawrence and Lorsch 1967; Sobrero and Schrader 1998; Koufteros, Vonderembse et al 2005) with an important insight towards extending it. The structural contingency framework suggests that aligning the cognitive frameworks of two organizations and developing common languages ought to have an impact on the effectiveness of the information exchange process (Sobrero and Schrader, 1998). This idea is consistent with the observation that manufacturers' knowledge boundary needs to be beyond the production boundary and into the specific knowledge of suppliers' tasks. Extending the knowledge overlap into the task responsibility of their suppliers enables assemblers to have a cognitive framework closer to that of the suppliers, thus facilitating information exchange and problem solving.

To complete the link between the structural contingency framework and the notion of knowledge portioning, one can recall an important distinction between architectural and component knowledge noted by Henderson and Clark (1990): Component knowledge relates to a physical part that is connected through a set of interfaces defined by architectural design. Architectural knowledge defines the way in which components are linked together while maintaining core design concepts. In their seminal paper, as well as many others that followed, an important distinction between these two types of knowledge has become very salient. For example, Henderson and Clark (1990) note that a technological shock that changes the product along one of these two dimensions may result in the demise of firms that have deficient knowledge in the evolving dimension.

When considering a complex system where an assembler subcontracts a number of firms to supply individual components, one expects a set of task partitioning, as well as a knowledge partitioning decisions. The assembler will concentrate on integration tasks, as well as, given the characterization of the previous paragraph, in architectural knowledge. In contrast, suppliers will focus on component tasks and knowledge. Nevertheless, for a given arrangement in terms of task partitioning, the level of knowledge partitioning can change. A given assembler may contract all the individual components of a system and only do the integration, but yet maintain a full staff of researchers and engineers that allows it to maintain detailed component knowledge. Other firms may choose not to do so. In general, assemblers will choose different levels of overlap towards component knowledge, evaluating the benefits that aligning cognitive frameworks provide to them in terms of information exchange effectiveness against the added cost that knowledge extension represents, for example in added engineering and research staff.

### **Uncertainty and Knowledge Partitions between Assemblers and Suppliers**

Uncertainty in the information processing framework is defined as the lack of information to perform the task (Galbraith 1977; Tatikonda and Rosenthal 2000; Premkumar, Ramamurthy et al. 2005). Literature in organization theory suggests that task uncertainty can be mitigated by strong communications and coordination mechanisms (Daft and Lengel 1986; Lawrence and Lorsch 1967). Tushman and Nadler (1978) claimed that “as work-related uncertainty increases, so does the need for increased amounts of information, and thus the need for increased information processing

capacity.” Recent empirical findings in product development research also support the idea that task uncertainty relate to greater need for communications and tight coordination (Petersen, Handfield et al. 2003; Tatikonda and Rosenthal 2000; Wasti and Liker 1997, 1999). Wasti and Liker’s (1999) study of the suppliers’ involvement in product development in the U.S. and the Japanese auto industry show that task uncertainty is a stronger predictor for supplier involvement in product design. Petersen and Handfield et al.’s (2003) more recent research on supplier integration in new product development also show that task uncertainty is associated with technology and cost information sharing.

These findings that task uncertainties relate with strong communication and coordination mechanisms suggest a need for a particular set of organizational arrangements that could deal effectively with the information processing requirements. In a business environment aiming to develop complex, multi-technology products, the key organizational characteristic is the presence of a system-integrating capability that maintains a loosely-coupled network structure with its specialized suppliers, “outsourcing detailed design and manufacturing while maintaining some level of in-house concept design and systems integration capabilities to coordinate the work (Brusoni, Prencipe et al. 2001).”

Yet, one needs to look beyond task partitioning and find also the best arrangement in terms of partitioning the knowledge between assembler and component makers. *In particular, one might expect that, in the face of increasing uncertainty, assemblers involved in inter-firm development will expand their knowledge boundary in directions*

*that allow them to better coordinate problem solving with their network of suppliers.* This perspective becomes salient in Takeishi's (2002) study of Japanese automakers and suppliers, whose results suggest that it is particularly important for automakers to have a higher level of component-specific knowledge when the project involves a new technology. The broader implication of Takeishi's (2002) results is that, despite an overall focus on knowledge at the architectural level, assemblers' system integration capability may be enhanced with greater knowledge in components, particularly when the project involves the task uncertainty associated with the development of new technologies. One can therefore state the first hypothesis to be tested empirically in this study:

***Hypothesis 1a:*** *Assemblers involved in inter-firm innovations with suppliers will be more likely to expand their component-specific knowledge domain when they encounter higher task uncertainties*

Yet, *hypothesis 1a* does not necessarily mean that assemblers will dominate component innovation under greater uncertainty. Rather, it claims that assemblers are *relatively* more likely to carry out component innovation in an environment under which assemblers are faced with uncertainties regarding technical success, especially when compared to periods of less uncertainty.

Similarly, the reverse logic can be used to suppliers. Higher level of architectural knowledge possessed by suppliers should facilitate problem solving with assemblers when the project involves new technologies. Although Takeishi (2002) did not specifically test this reverse dimension, he recognized that "building up architectural

knowledge about the component was recognized as a critical success factor for suppliers to win design competition.” Therefore, one can hypothesize that

***Hypothesis 1b:** Suppliers involved in inter-firm innovations with an assembler will be more likely to expand their architectural knowledge domain when they encounter higher task uncertainties.*

This perspective is consistent with the structural contingency framework: when facing uncertainty, assemblers move into the cognitive space of the suppliers and vice versa, facilitating information exchange and problem solving. Moreover, it provides a specific context to test the idea mentioned by Sobrero and Roberts (2002), according to which firms should adjust the nature of the information exchange over time to face different levels of task uncertainty.

### **Product Life Cycle and Knowledge Partitioning**

While idiosyncratic external factors in projects may drive the propositions presented above, one must also recognize that products – and their development – go through important development stages that influence in important ways the balance between architectural and component innovation in the supply chain. In particular, it is well established that the development of products and processes goes through a transition from an early “fluid” state to a highly rigid state (Clark 1985). The early “fluid” state can be described as one where product design and performance expectations are not clearly defined. A variety of different approaches and ideas for product and equipment designs are introduced to earn market acceptance. Experimentation with various designs



continues until a particular design achieves dominance (Anderson and Tushman 1990; Clark 1985; Henderson and Clark 1990; Suarez 2004; Tushman and Murmann 2002; Utterback 1996). Suarez (2004) explained the emergence of a dominant design as a result of competition among two or more alternative technological trajectories during five sequential milestones. Anderson and Tushman (1990) and later by Tushman and Murmann (2002) described the emergence of a dominant design as a main transition state between eras of ferment and eras of incremental innovation; and during the eras of ferment, technological variants compete for dominance.

Theories in dominant design research clearly emphasize the importance of architectural innovation in the early stage of technological developments before the emergence of a dominant design. This leads to hypothesis 2a:

***Hypothesis 2a:** Task uncertainties imposed on assemblers and suppliers involved in the early inter-firm technological development stage tend to induce overall architectural innovation.*

After the establishment of a dominant design, the evolutionary perspective further predicts rise of incremental innovation, especially in component parts (Utterback 1996). Once a major innovation is successfully introduced by innovation-leading firms, follower firms pursue imitation and further enhancement of the leading firms' success, changing the overall structure of the knowledge pattern (Mueller and Tilton 1969; Tushman and Murmann 2002; Utterback 1996).

Thus, after the emergence of a dominant design, innovation switches its attention to refining the established design (Clark 1985; Murmann and Frenken 2006; Tushman and Murmann 2002) as critical technical problems and product dimension of merit are determined (Tushman and Rosenkopf 1992). More importantly, focus of technological progress after the emergence of a dominant design typically lies at elaborating and extending the dominant design (Tushman and Rosenkopf 1992). Consequently, numerous incremental innovations around the established dominant design occur; and component knowledge gains greater importance (Henderson and Clark 1990). Metcalf (1995, pp. 36) states that: “Once a workable design configuration has been established, it provides a framework for incremental improvements within a stable broad knowledge and skill base.”

So, we have the following hypothesis:

***Hypothesis 2b:** Task uncertainties imposed on assemblers and suppliers involved in inter-firm technological development after the emergence of dominant design, tend to induce overall component innovation.*

## **METHODS**

As explained before, we will test the proposed hypothesis by investigating patenting by assemblers and suppliers in automotive emission control technologies. The empirical strategy is to use patents as a proxy to the knowledge space of both sides of the supply chain, looking at how they balance architectural and component-specific patents

in face of changing uncertainty at the task level. As explained below, this uncertainty will be assessed by characterizing the levels of stringency imposed through environmental regulation.

To implement this approach there are two steps. First, authors identify the relevant patents issued by the United States Patent and Trademark Office to be used as a proxy for innovative knowledge in both architectural and component innovation. The second step is the construction and execution of an econometric model to test the relevant hypotheses. The following sections detail the logic, procedures and models used for this test.

### **Design and Execution of Patent Screens**

The paper draws on patent data collected from the U.S. Patent and Trademark Office (USPTO). Patenting activity is used as a proxy for innovation. The relevant patent set for automotive emission control systems was developed by identifying successfully applied patents from 1970 to 1998. Authors used two approaches to generate the relevant patent set: an abstract-based keyword search and a class-based search. For the former, we selected seven different keywords: catalytic converter, emission, automobile, catalysts, pollution, exhausts, and engine. These keywords were then arranged in different combinations to search the U.S patent database electronically, yielding a preliminary set of potentially relevant patents. We then eliminated duplicate patents and screened out irrelevant patents by carefully reading abstracts of the generated patents. We often examined the “Assignee” and “Claims” portion of the patent because catalytic converter technologies can be related to non-automobile technologies such as power plants. To

generate relevant patent set using the class-based search method, we adopted patent subclasses representing catalytic converter technology from prior patent studies on catalytic converter technologies by Battelle Pacific Northwest Laboratory<sup>2</sup> (Campbell and Levine 1984). The process for obtaining the relevant patents using class-based search is similar to that of abstract-based keyword search: patents were pulled for 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 emission controls.

We combined relevant patents found from these two search methods; and generated longitudinal time-series patent database by extracting patent information, such as grant and application date, assignee, and country of origin.

### **Dependent variable**

Component innovation in automobile emission control technologies is the dependent variable in the analysis. Thus, a fundamental part of the proposed analysis involves the separation between architectural and component. Patents were categorized by linking the two generic definitions in the literature (Henderson and Clark 1990) to the specificities of the emission control technologies. **Table 1** shows key features of the patent categorization as either architecture or component.<sup>3</sup>

[Insert Table 1 here]

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<sup>2</sup> Battelle’s research on patenting activities on catalytic converter technologies used patent subclasses within two patent classes: Class 55 – Gas separation and Class 423 – Inorganic Chemistry

<sup>3</sup> This information is not part of the patent itself, requiring a separate categorization. A sound understanding of automotive emission control technologies is required to be able to properly perform such categorization.

Component innovation is associated with clearly identifiable physical portions of the system. Thus, inventions in the catalyst technology such as advanced catalysts and catalyst support materials are coded as component innovation. Innovations such as gas sensors from electronic feedback emission control technology, metal housing from manufacturing technology, and hydro-carbon (HC) absorber materials designed to reduce HC emission during the cold start from thermal control technology, were also categorized as component innovation. Architectural innovation integrates components into a whole system. Thus patents categorized as architectural innovation contain and/or address whole system-wide considerations. Architectural innovation includes the majority of innovations from electronic feedback emission control technology such as air-to-fuel ratio control, electronic exhaust gas recirculation (EGR), and catalytic converter efficiency monitoring. Dual-bed converter design, exhaust system design, cold-start up system, and electrically heated converter system are types of innovations that are categorized as architectural innovation.

### **Independent and Control Variables**

Organizational theorists explain task uncertainty as the lack of knowledge in accomplishing a task (Galbraith 1977; Daft and Lengel 1986). In an attempt to determine the characteristics of environments that influence decisions under uncertainty, Duncan (1972) identified three components of uncertainty as following: “(1) the lack of information regarding the environmental factors associated with a given decision making situation, (2) not knowing the outcome of a specific decision in terms of how much the organization would lose if the decision were incorrect, and (3) inability to assign

probability with any degree of confidence with regard to how environmental factors are going to affect the success or failure of the decision unit in performing its function.” The first two components of Duncan’s (1972) definition of uncertainty and Galbraith’s (1977) definition share a common theme, which is the general lack of information involved in decision making (Schrader, Riggs et al. 1993; Pich, Loch et al. 2002)

Following the definition of task uncertainty in the literature, recent research in product development operationalized task uncertainty using measures such as product novelty, project complexity, and extent of design changes (Wasti and Liker 1999; Tatikonda and Rosenthal 2000; Pich, Loch et al. 2002). But using a project metric to measure uncertainty would not work in the proposed analysis, mostly for two reasons. First, it would be impossible to assign individual patents to particular projects. Second, the projects tend to be endogenously determined by the supply chain partners themselves, making it hard to address causality between uncertainty and knowledge partitioning. Therefore, this research uses the fact that, since 1970, there have been several important technology-forcing regulations that imposed ever more strict emission standards on vehicle assemblers. The rationale is that, in each of these regulations, automakers were “forced” into achieving certain emission standards within established time frames. The important aspect for our research, though, is that it is widely acknowledged that automakers were unable to achieve these standards with existing technologies (Doyle 2000; Mondt 2000) This means that, at each stage, the industry entered an important period of technological uncertainty, which was resolved only when the products with the new technologies made it to the market. This uncertainty is akin to the idea of “lack of

knowledge in accomplishing a task” used in the information processing literature, and the basis for the construction of our set of hypothesis (Galbraith 1977).

Existence of technological uncertainties due to the presence of regulations was confirmed by interviews with industry experts who were involved in developing emission control technologies under the technology-forcing regulations. The following two excerpts from the industry experts exemplify the technical uncertainties implicit in the development of <sup>4</sup>new technologies to respond to the enactment of the Clean Air Act Amendments in 1970 (CAAA 1970): “In the late 1960s, they did not know how to do it. Catalysts came online in 1975, and research lab was spending a lot of time working on development of “after treatment systems.” And at the point in time when they adopted catalysts, they did not know how successful they would be. *So there always is risk associated with new technology.* (Expert A)”; “My guess is when that legislation [CAAA 1970] was passed; the engineers didn’t have a clue as to how to do that.” ..., “In fact we were building manufacturing facility to extrude substrates before we knew what the process was. We knew we had to have a factory... we didn’t know what we were going to make yet, nor how to make it. But we knew we needed to have a factory before we knew everything Otherwise we wouldn’t meet the deadline. (Expert B)”

The proposed evaluation uses the fact that the evolution of these regulations was not uniform over time, with periods of aggressive upgrading objectives followed by others with no required changes. This variation creates a unique opportunity test our hypothesis. Five distinct periods of time are used to operationalize the status of

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<sup>4</sup> Expert A and B possess more than 30 year experiences in automobile emission control system development from a domestic auto assembler firm and a catalyst substrate supplier firm respectively.

uncertainty. **Table 2** summarizes the rationale for determining each time period of uncertainty (*Uncertainty*). Each period is determined by considering the history of regulatory enactment and implementation: the enactment of the CAAA 1970 which led to the enactment of intermediate stringency in 1975<sup>5</sup> (*Uncertainty<sub>7075</sub>*); the enactment of the CAAA 1977 which delayed the phase-in of 90% pollution reduction requirements to 1981 (*Uncertainty<sub>7681</sub>*); the enactment of the CAAA 1990 which required further reductions in automotive pollutants by year 1994 (*Uncertainty<sub>9094</sub>*); and introduction of the National Low Emission Program (NLEV) in 1997 which was designed to adopt more stringent California Low Emission Vehicle (LEV) program nationwide (*Uncertainty<sub>9598</sub>*). Thus, since firms were under no regulatory pressures from 1982 to 1989 this represents *the period of least uncertainty or the period of certainty* (*Uncertainty<sub>8289</sub>*). **Figure 1** shows the evolution of federal automotive emission control stringencies and identifies periods of uncertainty that are used for the analysis.

[Insert Table 2 & Figure 1 here]

In addition to the status of the regulation, the annual number of successful patent applications (*PATENT*) in the same year of the focal patent is used as a control variable. The objective is to control for the potential impact of the amount of R&D firms devote to component innovation. Our concern is that the allocation of effort of firms to component and architecture innovation could be driven by the overall level of innovation effort associated to each period. By introducing this variable, we aim at eliminating this possibility. Summary statistics for these variables are presented in **Table 3**.

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<sup>5</sup> Government and industry agreed upon implementing intermediate level stringency in 1975, well below the stringency levels for automobile pollutants originally set forth in the Clean Air Act 1970



[Insert Table 3 here]

The other critical control variable is the nature of the patent assignee. As explained in the theory section, because of their responsibilities, assemblers (*ASSEM*) are more likely to invest, and hence to patent, in architectural technologies when compared to component technologies. Likewise, greater portion of suppliers' (*SUPP*) patenting activities are expected to be with component technologies.

### Econometric Model

A binomial probit model was used to estimate the impact of the independent variables on the probability of firms' doing component innovations. The generic model is specified in the following form:

$$P(Y_i = 1) = F[\alpha + \sum_T [\beta_T Uncertain_{Ti} + \delta_T (ASSEM_i * Uncertain_{Ti})] + \lambda PATENT_i + \varepsilon_i]$$

$$\text{or, alternatively } + \gamma_T (SUPP_i * Uncertain_{Ti})] + \lambda PATENT_i + \varepsilon_i]$$

where  $P(Y_i=1)$  is the probability that a patent  $i$  represents a component innovation<sup>6</sup>.  $F[.]$  is the cumulative normal distribution.  $T$  indicates five groups of aggregated regulation period dummy variables as related to the year that each patent was applied for (**Table 2**):  $T=7075$ ,  $T=7681$ ,  $T=8289$ ,  $T=9094$ , and  $T=9598$ .<sup>7</sup> As it can be noted, the patent assignee variables *ASSEM* (or *SUPP*) are omitted from the model as stand alone variables. Instead we included interaction terms with all regulation period dummy variables. We used this

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<sup>6</sup>  $Y_i = 0$  if a patent  $i$  represents an architectural innovation

<sup>7</sup> The period 9598 was used as a base group

less conventional representation because we were interested in observing interaction terms with the full range of periods in our data, from 1970 to 1998. We believe that this representation enables a better understanding of how firms' decisions to carry out component innovation shifts over time.

To test hypothesis 1, coefficients of interaction terms ( $ASSEM*Uncertain_T$  &  $SUPP*Uncertain_T$ ) of different periods are compared. As noted before, Period 8289 represents the period of less uncertainty. Thus, to support *hypothesis 1a*, coefficients of the interaction terms of assembler dummy with uncertainty ( $ASSEM*Uncertain_T$ ) for period 7075, 7681, 9094 and 9598 should be higher than that of 8289, suggesting relatively less investment in component knowledge in periods of certainty. The overall negative coefficients are an expected reflection of the fact that assemblers have more patents in architecture than in components. Similarly, to confirm *hypothesis 1b*, coefficients of interaction terms of supplier dummy with uncertainty ( $SUPP*Uncertain_T$ ) for period 7075, 7681, 9094 and 9598 should be smaller than that of period 8289, the period of less uncertainty. This would suggest relatively more investment in architectural knowledge in periods of uncertainty.

To test *Hypothesis 2*, the prevalence of architectural knowledge in the early phase of technological change (Clark 1985; Henderson and Clark 1990), the coefficients for various relevant periods are analyzed. According to hypothesis 2, coefficients for uncertainty in the early phase of technological change  $-Uncertain_{7075}$  and  $Uncertain_{7681}$ — should be negative as we expect to observe more architectural innovation

in the earlier phase of technological change in the 1970s compared to that of later part of technological change in the 1990s.

To build additional robustness into our analysis we also ran firm-level fixed effect regression models for assemblers and suppliers. The idea of separately run firm-level fixed effect regressions is to confirm that the patenting behaviors of lead assemblers and suppliers are similar to those exhibited by the full data set. We were concerned that unobserved firm level heterogeneity correlated with both time periods and component patenting could be driving our findings. Yet, it is also important to recognize that running separate fixed effects regressions for the two groups prevents a direct comparison of the relative patenting behavior of the groups over time. This limits our ability to test the relative impact of uncertainty periods in the two groups, an important part of the analysis.

The specification is now;

$$P(Y_{ij} = 1) = F[\alpha_j + \sum_T \beta_T Uncertain_{Tij} + \lambda PATENT_{ij} + \varepsilon_{ij}]$$

where  $P(Y_{ij} = 1)$  is the probability that the firm  $j$  performs innovation  $i$  that relates to component innovation.  $\alpha_j$  represent now the  $j$  firm fixed effect. The relative uncertainty effects found by using interaction terms (*ASSEM* or *SUPP* interacted with uncertainty periods) are suppressed as assemblers and suppliers' patent set are regressed separately.

To incorporate firm fixed effect, each patenting firm is identified. Out of a total of 239 patenting firms, we kept those that had more than one patent per year. Thus, our fixed-effect regressions have 16 patenting firms (6 assemblers and 10 suppliers). The top six patenting assemblers are Toyota, Ford, General Motors, Nissan, Honda, and Mazda

Motors. The top ten patenting suppliers are Engelhard, W.R. Grace, Corning, Nippondenso, EMITEC GmbH, NGK insulators, Robert Bosch, Universal Oil Production Company, Hitachi, and SIEMENS.<sup>8</sup>

## RESULTS

**Table 4** shows the results of regressions for the complete data set. First, to examine *hypothesis 1a* and *1b*, we look at Models 2 and 3, specifically the coefficients for the interaction between Assembler and uncertainty periods (Model 2), or Suppliers and uncertainties (Model 3). As it can be seen, the dummy coefficient for the interaction of assembler and period of uncertainty ( $ASSEM*Uncertain_t$ ) is smaller (more negative) for the period 8289 than for other periods. More negative interaction coefficient indicates greater relative propensity to carry out architectural innovation. Thus, the result supports the idea that assemblers tend to concentrate relatively more on their core expertise, that is, architectural innovation in time of less uncertainty, and expand their knowledge domain in components when they face higher task uncertainties. Similarly, coefficients for  $SUPP*Uncertain_t$  for the period 8289 in Model 3 is found to be greater than those of other time periods, confirming the notion that, in periods of higher task uncertainty, suppliers expand their knowledge domain in product architectures to a relative greater degree. Moreover, Wald tests show that differences in interaction coefficients between those associated with uncertainty in 8289 period and coefficients in other periods are always significant. These results support *hypothesis 1a* and *hypothesis 1b*.

[Insert Table 4 here]

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<sup>8</sup> Top 6 assemblers and 10 suppliers account for approximately 80% and 42% of overall patenting activities of assemblers and suppliers respectively.

The regressions also partially confirm *hypothesis 2a* – that architectural innovation prevails in the early phase of technological changes. As it can be seen, the coefficients for uncertainty during the period 7075 and 7681 are negative and significant in any of the models (1, 2 or 3) in Table 4. This result is consistent with the history of automobile emission control technologies. A reasonable dominant design for automobile emission control can be considered to be the electronic-feedback-controlled catalytic converter with three-way catalysts (TWC) introduced in 1981. Prior to 1970s, catalytic converters were used in non-automobile sectors such as chemical plants. In the early seventies, assemblers and suppliers in the auto industry were focusing on coming up with catalytic converters suitable for automobile application.<sup>9</sup> The catalytic converter introduced in 1975 was equipped with only oxidation catalyst and was incapable of reducing harmful NO<sub>x</sub>. Different catalytic converter design such as a dual catalytic converter system was introduced after 1975 to control for NO<sub>x</sub> as well as HC and CO (Heck and Farrauto 1994). Yet, the industry came up with a dominant design in 1981, the catalytic converter system equipped with TWC that converts all three pollutants simultaneously. After the introduction of catalytic converter designs equipped with TWC, innovation in automobile emission control mainly shifted to improving efficiency and reliability of systems such as refining catalyst compositions (Heck and Farrauto 1994).

Yet, as it can also be observed in Table 4, the coefficients for the periods of uncertainty 8289 and 9094 are mostly not statistically different from zero (except in

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<sup>9</sup> In addition to automobile tail pipe emission reduction requirements imposed by the U.S. Environmental Protection Agency (EPA), the automobile industry was also mandated to improve corporate average fuel economy (CAFÉ) standards (Thorpe 1997; Kleit 2004). The CAFÉ program which was enacted in 1975 resulted in imposing *conflicting* requirements of emission control and fuel economy on the automobile industry (Ettlie and Rubenstein 1981). Nevertheless, EPA's efforts in *forcing* innovation in emission control were successful (Mondt 2000; Lee, Veloso et al. 2004).

Model 2 where the 8289 coefficient is positive and significant). This means that they are not dissimilar from the baseline, which is the period 95-98. Overall, this indicates that there is a greater propensity to perform component innovation starting in 1982 when compared to that of 1970s and this propensity is probably the highest in the eighties. Thus, contrary to what one would expect, after the change in the early eighties, the propensity for component innovation did not continue to grow over time as the technology apparently further matured, providing only weak support for *hypothesis 2b*.

This finding may be understood by reflecting on the nature of the Clean Air Act Amendments of 1990 (CAAA 1990). The Clean Air Act Amendment introduced in 1990 required even more stringent standard to the auto industry. To meet the more stringent standard imposed by the CAAA 1990, auto makers and suppliers developed thermal control technologies that allowed them to reduce emissions during the cold-start and adopted more advanced electronic control technologies. Although innovations during the 1990s took place around the dominant TWC design, the CAAA 1990 generated a new round of important architectural innovation associated with thermal control technologies, lessening the expected impact of the post-dominant design stage on inducing overall component innovation.

[Insert Table 5 here]

The results described above show how product life and task uncertainties are conditioning innovation patterns among suppliers and assemblers over the entire period in relative terms (i.e. assembler component innovation in a given uncertainty period relative to that of suppliers in the same period and that of both types of firms in other

uncertainty periods). But it is also relevant to estimate the total profile of component innovation by assemblers and suppliers over the entire period. This estimation allows considering the compound influence of product life cycle and task uncertainty in component innovation for each type of firms, while ignoring their relative evolution. Total effect for each period, presented in Table 5, is estimated by adding coefficients of period dummy, interaction term, and constant term--  $(\alpha + \beta_T + \delta_T)$  for assemblers and  $(\alpha + \beta_T + \gamma_T)$  suppliers.

Several results arise from this analysis. First, the coefficients of interaction terms for assemblers ( $\delta_T$  in Table 4) are all negative while the equivalent ones for suppliers ( $\gamma_T$  in Table 4) are positive. This implies, as one might expect, that assemblers and suppliers have architectural and component innovation as their main course of actions respectively. Second, the values suggest that the overall propensity for component innovation follows a pattern similar to the relative assessment described above when discussing Hypotheses 1a/b. This suggests that the effect of task uncertainty dominates, so that the highest level of component innovation for suppliers happens in the 82-89 period, that with least uncertainty. But the overall propensity of assemblers for component innovation increases continuously over time, as product life cycle evolves (Table 5). In particular, architectural innovation does not dominate in the 82-89 period. This means that the important role of architectural innovation for assemblers in the 82-89 period, noted above, is significant only to the extent that there is a big overall shift towards component innovation, mostly driven by suppliers. This suggests that lifecycle effects may dominate over the task uncertainty effects in determining the propensity for component vs. architectural innovation for assemblers.

[Insert Table 6 here]

Finally, **Table 6** shows results of fixed-effect regressions using separate patent datasets for assemblers and suppliers<sup>10</sup>. The fixed-effect regression results confirm the early results for total estimation (Table 5). Regression coefficients for assemblers' patent set increase continuously throughout, confirming assemblers' propensity to increase component innovation over time. Furthermore, regression coefficients for suppliers' patent set also follow the trend found in the full patent set, that is, the propensity for component innovation for suppliers is highest during the *Uncertain*<sub>8289</sub> period—the period of least uncertainty.<sup>11</sup> This proximity of results with the total sample and only with the lead suppliers and assemblers suggest that unobserved heterogeneity is not driving our findings.

## DISCUSSION AND CONCLUSION

This research looks at the development of automotive emission control technologies over a twenty-eight year period. The development of these complex multi-technology products involves a network of suppliers and assemblers. Assemblers typically maintain a loosely-coupled network of suppliers by “outsourcing detailed design and manufacturing to specialized suppliers while maintaining in-house concept design and systems integration capabilities to coordinate the work (Brusoni et al. 2001).” In such

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<sup>10</sup> As explained in the previous section, the fixed effects analysis of Table 6 only allows a comparison with the total effects reported in Table 5, and not a direct evaluation of the relative effects for the two types of firms, as presented in Table 4

<sup>11</sup> Signs of corresponding regression coefficients for period dummies for fixed effect regressions (**Table 6**) also agree with those found by total effect estimation using full patent sample (**Table 5**) when the coefficient for the constant term is added to the coefficient of each period dummy, providing additional support for their agreement.



context where the buyer is an integrator sourcing components from a diverse set of suppliers, the knowledge base of the buyer tends to focus relatively more on architectural knowledge, while the suppliers dominate component knowledge.

This study uses patents in automotive emission control technologies to analyze the impact of uncertainty on firms' decisions to adjust their knowledge base. Patents were categorized into architectural and component-specific innovation, and technology-forcing regulations imposed by government on firms in auto industry from 1970 to 1998 were used to define periods of high and low uncertainty.<sup>12</sup> Results show that, under task uncertainty, assemblers expand their knowledge base relatively more into components and component makers into architectural knowledge. The findings that assemblers expand their knowledge footprint in components lend support to prior observations that firms' knowledge boundaries extend beyond their task boundaries. They also support and extend our understanding of the structural contingency framework. Firms' expansion of their knowledge boundaries beyond their task boundaries reflects their need to develop common languages among partners to facilitate more effective information exchanges between partners involved in inter-firm product developments and resolve task uncertainties. We show that this is particularly true in what concerns architectural and component knowledge.

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<sup>12</sup> The paper does not cover trend in the early 2000. Since the 1990s, firms incorporated more sophisticated electronic components to the system to improve the overall emission control capabilities. Yet, key architecture of the emission control system—catalyst-driven emission control-- remain the same. Consequently, we believe that the trend in the early 2000 would not deviate from that of early periods from 1970s to 1998.

This study implies the importance of expanding knowledge base beyond task boundary especially when firms are involved in developing technologies that are relatively unfamiliar or new to their existing product base. Assemblers and component suppliers' consistent pattern of knowledge-partitioning allude that assemblers (suppliers) possessed active R&D staffs involved in components (system architectures) for project involving new technologies. Detailed mechanisms for acquiring and maintaining knowledge is still subject to further research; yet this finding suggests that assemblers as well as suppliers may need to develop internal R&D capabilities devoted to areas beyond their production domain in order to remain competitive in technological race. This may mean that assemblers may need its own R&D staffs working on critical components outsourced to suppliers and suppliers may also need R&D staffs on system architecture in order to be more competitive and effective. Especially the finding that the assemblers' propensity for component research increased over the life cycle of product evolution further strengthens the argument for the importance of acquiring and effectively maintaining internal R&D capability in component when developing products jointly with suppliers.

This work makes several contributions to the literature. First, by examining coordination of knowledge partitioning practices in this multi-component, multi-technology product under varying levels of regulatory pressure, this research provides critical insights as to how inter-firm knowledge is managed in highly uncertain innovation environments. Second, this work contributes to the literature on product development by providing both a theoretical approach and a longitudinal empirical examination of the link between task uncertainties and firms' decision to partition their

knowledge base in the course of inter-firm product developments, offering a more dynamic view of knowledge partitioning, especially with regard to evolution of technological change. In fact, an important finding of this research is that, in addition to task uncertainty, there is another force - product life cycle - which influences knowledge management practices and boundaries for assemblers and suppliers. Technological artifacts go through extensive architectural innovation in the early product life cycle phases, but its importance withers as the technology evolves over time as both assemblers and suppliers increase their knowledge in components over the succession of uncertainty periods. Moreover, the observation that assemblers consistently increase their knowledge base in components as the technology matures implies that the effect of product life cycle may dominate over that of task uncertainty for assemblers.

Finally, by establishing a relationship between task uncertainties and firms' endeavor to build up capabilities through either architectural and/or component innovation, this research builds on Henderson and Clark's (1990) notion that both architectural and component knowledge are important in building up firms' capabilities and explores how they change depending on the task characteristics and environment. In particular, this research empirically supports the structural contingency framework idea that assemblers and suppliers may strengthen information exchange effectiveness in inter-firm innovation environments by strategically aligning their cognitive framework; in this case, choosing different levels of knowledge overlap by expanding their knowledge space in component and system architectures for assemblers and suppliers respectively depending on the level of task uncertainties and the stage of technological evolution.

It is important to recognize that there are limitations in this research. First, the analysis does not take into account potential and very plausible influences of specific knowledge sharing routines within the network of assemblers and suppliers in the auto industry. There has been significant convergence between the U.S. and Japanese auto industry in the way assemblers and suppliers co-work (Helper and Sako 1995; Liker, Kamath et al. 1996; Kotabe, Martin et al. 2003). Although not as extensively as Japanese automakers, U.S. assemblers and suppliers have somehow moved toward longer-term, more trust-based relationships from their traditional arms-length contract relationships. This suggests that networks of suppliers could play an important role in building up assemblers' in-house component innovation capabilities (Dyer and Singh, 1998; Dyer and Hatch 2006). Yet, this research does not offer a better understanding of how specific procedural mechanisms employed by assemblers and suppliers helps them exchanging knowledge and problem solving. Further research could explore this issue of how knowledge sharing routines among the network of assemblers and suppliers influence assemblers' and/or suppliers' decisions to expand their knowledge domains outside of their main expertise.

The analysis in this paper also does not consider inter-relationships between the architectural design of the product and component knowledge (Ulrich 1995). Design architecture may have an important influence on knowledge partitioning (Fine and Whitney 1998; Takeishi 2002). Products with different modularity<sup>13</sup> may confer different

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<sup>13</sup> Degree to which functional elements of the product is coupled with physical components of the product (Ulrich 1995).

strategic choices to assemblers. For example, Brusoni et al. (2001) claim that product interdependencies among subsystems or components may have different implications for managing organizational couplings, implying that product modularity influences assembler's role as a system integrator. A more in-depth study of how products differ in levels of modularity and how such aspect influences firms' decision to expand their knowledge domain in components, would significantly enhance our understandings of the role knowledge boundaries play in firms' competitiveness.

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**TABLE 1****Patent Categorization**

Innovation	Knowledge Dimension
Catalyst materials	Component
Washcoat materials	Component
Catalyst support materials	Component
NOx Trapping Catalyst Materials	Component
Mounting Materials	Component
Porous catalytic carrier	Component
Palladium three-way catalysts	Component
Air-to-Fuel Ratio Control	Architecture
Electronic EGR	Architecture
Secondary Air Control System	Architecture
Spark Time Control	Architecture
Catalytic converter efficiency monitoring	Architecture
Catalytic converter deterioration monitoring	Architecture
Sensors (emission and/or temperature)	Component
Exhaust system design	Architecture
Catalytic converter housing design	Component
Dual bed converter design	Architecture
Metal housing	Component
Mounting materials	Component
Catalyst carrier body	Component
Cold start-up system	Architecture
Electrically heated converter (EHC) system	Architecture
Warm-up converter	Component
Fuel burner type converter heater system	Architecture
Absorber materials	Component

**TABLE 2**

**Period Dummy Variables and Rationale for Embedded Uncertainty**

<b>Variables</b>	<b>Description</b>
<i>Uncertain<sub>7075</sub></i>	<ul style="list-style-type: none"> <li>● Period of <i>Uncertainty</i> from 1970 to 1975.</li> <li>● Government enacted the Clean Air Act Amendment in 1970 which 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).</li> <li>● Catalytic converter based on oxidation catalysts was introduced in 1975</li> </ul>
<i>Uncertain<sub>7681</sub></i>	<ul style="list-style-type: none"> <li>● Period of <i>Uncertainty</i> from 1976 to 1981.</li> <li>● Government enacted the Clean Air Act Amendment in 1977 which delayed the HC standard until 1980, and the CO and NO<sub>x</sub> standards to 1981. The 1981 NO<sub>x</sub> requirement was relaxed to 1 g/mi</li> <li>● Catalytic converter based on three-way catalysts (TWC) was introduced in 1980</li> </ul>
<i>Uncertain<sub>8289</sub></i>	<ul style="list-style-type: none"> <li>● Period of <i>Uncertainty</i> from 1982 to 1989</li> <li>● Period of least uncertainty: Firms were under no regulatory pressures from 1982 to 1989</li> </ul>
<i>Uncertain<sub>9094</sub></i>	<ul style="list-style-type: none"> <li>● Period of <i>Uncertainty</i> from 1990 to 1994.</li> <li>● Government enacted the Clean Air Act Amendment in 1990</li> <li>● Congress required further reductions in HC, CO, NO<sub>x</sub> and particulate emissions.</li> </ul> <p>(short-term lowering of HC and NO<sub>x</sub> by 39%, and longer-term lowering of HC by 70%, CO by 50%, and NO<sub>x</sub> by 80% relative to 1990 levels)</p>
<i>Uncertain<sub>9598</sub></i>	<ul style="list-style-type: none"> <li>● Period of <i>Uncertainty</i> from 1995 to 1998</li> <li>● Firms encountered NLEV program in 1977 designed to adopt more stringent California LEV program nationwide, started initially with northeast ozone transport regions.</li> </ul> <p>1999: 40% TLEV, 30% LEV, 30% TIER 1                  2000: 40% TLEV, 60% LEV                  2001: LEV standard</p>

Tier 1: 0.25g/mi HC, 3.4g/mi CO, 0.4g/mi NO<sub>x</sub>

TLEV (Transitional Low Emission Vehicle): 0.125 g/mi NMOG, 3.4 g/mi CO, 0.4 g/mi NO<sub>x</sub>

LEV (Low Emission Vehicle): 0.075g/mi NMOG, 3.4g/mi CO, 0.2g/mi NO<sub>x</sub>

Source: (EPA 1997; Mondt 2000)

**TABLE 3****Summary Statistics for Variables used for Regression Analysis**Number of observations:  
2102

Variable	Description	Mean	Min.	Max.	S.D.
<i>PATENT</i>	Number of yearly successful patent application	103.2	12.0	164.0	51.6
<i>COMP</i>	Component Innovation Dummy	(D=1: 1210 observations)			
<i>ASSEM</i>	Assembler Dummy	(D=1: 953 observations)			
<i>SUPP</i>	Supplier Dummy	(D=1: 1149 observations)			
<i>Uncertain<sub>7075</sub></i>	1970-75: Dummy	(D=1: 330 observations)			
<i>Uncertain<sub>7681</sub></i>	1976-81: Dummy	(D=1: 252 observations)			
<i>Uncertain<sub>8289</sub></i>	1982-89: Dummy	(D=1: 238 observations)			
<i>Uncertain<sub>9094</sub></i>	1990-94: Dummy	(D=1: 613 observations)			
<i>Uncertain<sub>9598</sub></i>	1995-98: Dummy	(D=1: 668 observations)			

**TABLE 4**  
**Regression Results**

Dependent Variable: Component Innovation (patent) [0,1]

Model No.	1	2	3
<b>Variables</b>			
<i>Uncertain</i> <sub>7075</sub>	-0.513 (0.161)***	-0.456 (0.180)**	-0.803 (0.199)***
<i>Uncertain</i> <sub>7681</sub>	-0.526 (0.184)***	-0.451 (0.212)**	-0.539 (0.207)***
<i>Uncertain</i> <sub>8289</sub>	0.247 (0.211)	0.961 (0.273)***	-0.232 (0.238)
<i>Uncertain</i> <sub>9094</sub>	0.047 (0.086)	0.169 (0.115)	-0.066 (0.111)
<i>PATENT</i>	-0.004 (0.001)***	-0.004 (0.001)**	-0.004 (0.001)**
<i>ASSEM* Uncertain</i> <sub>7075</sub>		-0.773 (0.153)***	
<i>ASSEM* Uncertain</i> <sub>7681</sub>		-0.515 (0.160)***	
<i>ASSEM* Uncertain</i> <sub>8289</sub>		-1.620 (0.228)***	
<i>ASSEM* Uncertain</i> <sub>9094</sub>		-0.662 (0.105)***	
<i>ASSEM* Uncertain</i> <sub>9598</sub>		-0.434 (0.098)***	
<i>SUPP* Uncertain</i> <sub>7075</sub>			0.773 (0.153)***
<i>SUPP* Uncertain</i> <sub>7681</sub>			0.515 (0.160)***
<i>SUPP* Uncertain</i> <sub>8289</sub>			1.620 (0.228)***
<i>SUPP* Uncertain</i> <sub>9094</sub>			0.662 (0.105)***
<i>SUPP* Uncertain</i> <sub>9598</sub>			0.419 (0.098)***
<b>Constant</b>	0.719 (0.229)***	0.890 (0.241)***	0.463 (0.238)**
<b>N</b>	2,102	2,102	2,102

Standard errors in parentheses

\*: p-value<0.1; \*\*: p-value<0.05; \*\*\*: p-value<0.01

**TABLE 5** **$(\alpha + \beta_T + \delta_T)$  and  $(\alpha + \beta_T + \gamma_T)$  Coefficients for Total Effect Estimations**

Period	Assemblers	Suppliers
	$\alpha + \beta_T + \delta_T$	$\alpha + \beta_T + \gamma_T$
1970-1975 (7075)	-0.339 (4.71)**	0.433 (12.56)***
1976-1981 (7681)	-0.076 (0.33)	0.438 (11.19)***
1982-1989 (8289)	0.231 (2.79)*	1.850 (93.47)***
1990-1994 (9094)	0.397 (4.14)**	1.058 (29.85)***
1995-1998 (9598)	0.456 (3.67)*	0.881 (13.42)***

Chi-square statistics for Wald tests testing  $\alpha + \beta_T + \delta_T = 0$  in parenthesis

\*: p-value&lt;0.1; \*\*: p-value&lt;0.05; \*\*\*: p-value&lt;0.01



**TABLE 6****Regression Results with Firm Fixed Effect**

Dependent Variable: Component Innovation (patent) [0,1]

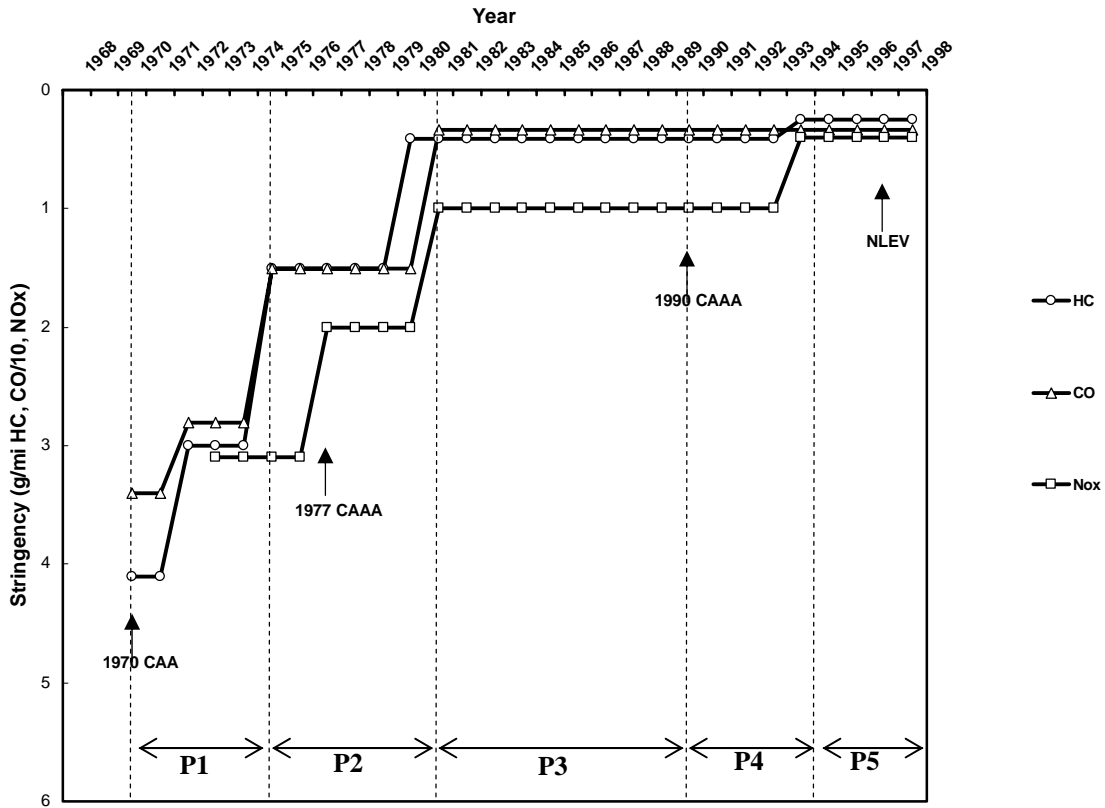
Variables	Assembler Patent Set	Supplier Patent Set
<i>Uncertain</i> <sub>7075</sub>	-1.502 (0.354)***	-0.736 (0.397)**
<i>Uncertain</i> <sub>7681</sub>	-0.855 (0.363)**	-0.593 (0.463)
<i>Uncertain</i> <sub>8289</sub>	-0.227 (0.417)	1.914 (0.639)***
<i>Uncertain</i> <sub>9094</sub>	-0.037 (0.158)	0.365 (0.225)*
<i>PATENT</i>	-0.004 (0.004)	-0.004 (0.004)
N	953	1,149

Standard errors in parentheses

\*: p-value&lt;0.1; \*\*: p-value&lt;0.05; \*\*\*: p-value&lt;0.01

**FIGURE 1**

**Periods of Uncertainty and Certainty**



Periods of uncertainty are determined by considering federal regulations on automotive emission control. Changes in the required stringency levels and the timing of enactment of regulations are shown in the figures. Periods of *uncertainty* used for the analysis is as follows: P1: PERIOD<sub>7075</sub>, P2: PERIOD<sub>7681</sub>, P3: PERIOD<sub>8289</sub>, P4: PERIOD<sub>9094</sub> and P5: PERIOD<sub>9598</sub>.