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# Capturing Benefits from Tomorrow's Technology in Today's Products: The Effect of Absorptive Capacity

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Abstract

In this paper, I propose and examine a specific means by which firm R&D experience may be helping firms to improve their current-technology products: Firms that conduct future-technology R&D may be better at adapting components from related future technologies for use in their current-technology products. I use patent data to test whether automobile carburetor suppliers with higher levels of future-technology R&D activity are better at adapting components from related future technologies for use in carburetors.

## 1. Introduction

Scholars have long recognized that firms may receive certain benefits from inventing and working with future technologies. Quite apart from the direct benefits firms gain from experience with future technologies, such as moving down learning curves more quickly than competitors and creating temporary monopolies, stands a class of indirect benefits to firm competitiveness. For instance, Baldwin (1962) shows that firms with their own Research and Development (R&D) functions are better able to make use of related outside research. Rosenberg (1970) makes a similar point about the international transfer of technology. Cohen and Levinthal base their "Absorptive Capacity" theory on these ideas, examining the cognitive and organizational mechanisms underlying absorptive capacity, concluding that a firm's "ability to evaluate and utilize outside knowledge is largely a function of the level of prior related knowledge" (1990). Little attention has been devoted, however, to the exploration of how technologies benefit from a firm's "prior related knowledge." In other words, if we focus our attention on a specific product or technology, how does a firm's absorptive capacity improve that product or technology? In this paper, I propose and examine a specific means by which firm absorptive capacity may be helping firms to improve their current-technology products: Firms that gain experience working with future technologies may be better at adapting components from related future technologies for use in their current-technology products. The focus in this paper is on the adaptation of a component of a "radical innovation" technology for use in a current-technology product. I use the terms "future technology" and "next-generation" in this paper to refer to a "radical innovation" replacement for the current-technology product.

The question of whether experience inventing and working with future technologies helps firms' current products is part of the larger question of whether firms can appropriate the returns from this inventive activity. The intellectual property (IP) generated by inventive activity may be difficult to protect for a number of reasons. For example, competitors may be able to copy much of a new technology while "inventing around" patent-protected portions of the technology. Also, some types of intellectual property are more difficult to protect—in most cases, product innovations are more open to examination by competitors than are process innovations. Much of the difficulty of appropriating returns from inventive activity is a result of "free-riding" by other firms, which presumably affects firm future technology investment decisions.[1]

I use patent data from (Hall et al. 2001) to test whether firms with higher levels of future-technology experience activity are better at adapting components from related future technologies for use in current generation products. I find that when firms have more experience working with a future technology, they are better at adapting components from related future technologies for use in current generation technology products. This finding holds both within individual firms over time and in comparisons between firms. I also find that when firms have more experience working with a future technology, they are more likely to adapt components from related future technologies for use in current generation technology products. Finally, I find preliminary evidence that suggests that those future-technology invention activities must be sufficiently closely related to the current-technology product for them to have an effect on the current-technology product's absorption of the component from the future technology.

This paper proceeds as follows. Section 2 is a discussion of the literature and theory. Section 3 provides background on automobile carburetors, and Section 4 describes the data. Estimation and identification are discussed in Section 5, empirical results are presented in Section 6, and Section 7 concludes.

## 2 Literature Review and Theoretical Discussion

Firms that gain experience with future technologies and that conduct R&D seem to be better at recognizing and exploiting innovations originating outside the firm. Baldwin (1962), Tilton (1971), and Mowery (1983) show that firms that conduct R&D are better able to make use of related outside research. Rosenberg (1970) and Teece (1977) make similar points about the international transfer of technology. Others have proposed that absorptive capacity may be developed by participating in activities other than R&D. Abernathy (1978) and Rosenberg (1982) suggest that manufacturing experience can improve a firm's ability to utilize outside innovations related to the products it manufactures. The "Absorptive Capacity" theory advanced by Cohen and Levinthal

[1] The free-rider problem serves as one of the principal motivations for the public financing of R&D.

similarly proposes that a firm's "prior knowledge permits the assimilation and exploitation of new knowledge" (1990). Cohen and Levinthal's discussion of absorptive capacity focuses on the cognitive and organizational mechanisms underlying absorptive capacity. They say that individuals' ability to understand and exploit new and unfamiliar technologies may be improved by the experience gained from working with new (and, implicitly, related) technologies. Organizations may also benefit from prior experience with new, related technologies, because experience builds innovation-friendly structures and norms within organizations, making it more likely that they will be able to exploit new technologies in the future. Cohen and Levinthal (1994) subsequently offer a formal model of absorptive capacity which predicts that absorptive capacity will benefit firms not only in their ability to exploit new technologies, but also in their ability to assess more accurately the value of new, related technologies invented by others.

Though the behavioral and organizational mechanisms by which firms accumulate absorptive capacity are well understood, there have been relatively few empirical studies of how experience working with future technologies actually improves a firm's products. In other words, although it is clear that people and organizations gain experience from working with new technologies, the process by which the fruits of "exploring" activities come to be "exploited," are not clearly understood. One exception is Hatch and Mowery (1998), which identifies specific mechanisms responsible for improvement in production technologies.

In this paper, I examine the transfer of components from future technologies to current ones. I focus on the question of whether a firm's experience with future technologies affects the efficiency with which it adapts future-technology-derived components for use in current-technology products. The component nature of technologies is key to this argument. One stream of literature devoted to modularity in technological innovation has examined how component technologies interact and how they affect firm performance (Baldwin and Clark 2000). Alwyn Young (1993) proposes a model of endogenous innovation in which final goods improve as the intermediate goods of which they are composed improve. The idea of "blending" new and old technologies to obtain some final product with desirable efficiency properties appears in the economic development literature, too (1988). Christensen (1997) mentions the hybridization of old and new technologies, as does Foster (1986).

In Snow (2006), I find that current-technology carburetors from automobile firms that "make" their own future technology products (Electronic Fuel Injection) improve more rapidly after the introduction of the new technology. That result seems to support the notion that firms' current-technology products benefit from future-technology R&D, but it is not an explicit test of that hypothesis. In that work, I did not observe firms' inventive activities, but rather I used their future product mix to impute their current inventive activity, and the methodology focused on changes over time in carburetor technology and mileage rather than on absolute carburetor performance levels. Furthermore, I was able to identify only two carburetor manufacturers for the empirical tests in that paper.

In this paper, I propose the existence of a type of technological improvement that may result from increased absorptive capacity. Although I do not focus on the means by which absorptive capacity is accumulated within firms, one can imagine at least two means by which experience working with future technologies could lead to the technology transfers under examination here. First, engineers and scientists who work to develop future technologies learn about the possibilities and limitations of the future technologies. They therefore become better prepared to recognize areas in which components of those new technologies may be adapted for use in current-technology products. Not only do they become better at recognizing opportunities, but they also become better at adapting those components for use in current-technology products.

A second example is an organizational one: A firm that invents future technologies develops structures and processes by which to translate inventions into usable products. This may take the form of periodic transfers of personnel between R&D functions more closely related to current products, or it may take the form of formal organizational liaison between R&D and product development. In any case, firm resources related to current-technology products are brought into contact with firm resources related to future-technology products, thereby making recognition and transfer of technologies more likely and more effective. Again, the focus of this paper is not the cognitive and organizational mechanisms by which absorptive capacity is built. Rather, the focus of this paper is on one means by which absorptive capacity might be expected to translate into observable improvements in current products.

## 3 Carburetors

This paper focuses on automobile carburetor firms, their inventive activity, and their products that benefited from that activity. Automobile carburetors are devices that mix gasoline and air in a controlled ratio so that the mixture may be burned in an automobile engine's combustion chamber, thus creating the force that moves the automobile. A carburetor's efficiency, as measured by its fuel consumption and by the tailpipe emissions it allows, depends upon its ability to control this air/fuel ratio. The control of this ratio is difficult because the conditions under which it must be performed can vary widely. Engine speed and throttle position have a large effect on this ratio, and other factors such as air temperature, relative humidity, engine temperature, car age, driving style, and fuel quality can also affect carburetor performance. Until the mid-1980s, most carmakers used carburetors to deliver fuel and air into their cars' combustion chambers. Carburetor performance grew in importance to automobile firms during the 1970s and 1980s as the United States Environmental Protection Agency (EPA) imposed increasingly strict regulations on the fuel consumption and emissions performance of automobiles sold in the United States.

In response to these tightening regulations, automobile manufacturers and their suppliers introduced a more efficient direct substitute for carburetors called Electronic Fuel Injection (EFI). EFI was a "radical innovation" relative to the existing carburetor and mechanical fuel injection technology.[2] The first EFI systems appeared in 1983, and gradually began to displace carburetors from the market. Soon after the introduction of EFI, carburetor companies adapted for use in carburetors a technology first developed for use in EFI systems. This technology was called the Feedback Fuel System (FFS), and it consisted of electronic components which observed engine performance in real time and updated the EFI system's operating parameters to obtain the most efficient fuel/air ratio

[2] Even apart from the electronics, EFI was radically different from mechanical fuel injection. Mechanical fuel injection's use was limited to a few high-end and racing automobiles, and it does not figure in the analysis in this paper.

given the current operating conditions. The first FFS electronics were invented by Bendix and Bosch, two automobile parts suppliers. None of the carburetor firms I examine in this paper invented FFS electronics, but all of them had experience with EFI-related inventive activity. Although FFS was originally developed for EFI, and although carburetors were not ideally suited to the addition of FFS components, carburetor performance nevertheless benefited from FFS electronics. This led to a new hybrid type of fuel delivery device, the FFS-equipped carburetor, which came to market in the mid-1980s. This type of carburetor was produced by a variety of carburetor manufacturers which also varied in their levels of involvement in EFI-related inventive activity. It is the variation in level of inventive activity that I will use to test whether firm experience with inventive activity in EFI affected the likelihood and performance of that adaptation of FFS for use in carburetors.

As a methodological note, carburetor efficiency can be measured in several different ways. In this study, I measure carburetor efficiency using automobile fuel consumption, although carburetor design also affects emissions performance and drivability. I use fuel consumption for the following reasons. Marginal improvements in fuel consumption were rewarded by consumer markets (Kahn 1986). Perhaps more importantly, marginal improvements in fuel consumption were rewarded by government regulators under the Corporate Average Fuel Economy (CAFE) program, in which manufacturers could apply credit from more-fuel-efficient models to less-fuel-efficient models to avoid fines. Carburetor emissions performance, on the other hand, was an all-or-nothing proposition from the EPA's perspective—a car met standards or it didn't, and the manufacturer was given no credit by regulators for overachieving. Furthermore, during the period of observation, it was very difficult for a consumer to discover the emissions performance level of a given automobile.[3] From the researcher's point of view, carburetor emissions performance is impossible to separate from the performance of other emissions control components, which are unobserved in the data. Another candidate for measuring carburetor performance, drivability, is difficult to operationalize,

[3] Automobile emissions information is now available to consumers via the Internet

and it is not observed in these data.[4] For these reasons, fuel efficiency is the metric that best measures a carburetor's performance in its intended role. So, for the purposes of this paper, I define carburetor efficiency as the fuel consumption performance measured as Miles Per Gallon (MPG) of a carburetor-equipped car, after controlling for all of the other attributes of the car that may be expected to affect MPG.

## 4 Data

In this paper, I use data from four sources. The first dataset comes from the US Environmental Protection Agency. This dataset lists each type of car model that was sold in the United States for the automobile model years 1978 through 1992 and that was equipped with a carburetor. The unit of observation is a car model, which is any available combination of model name, body type, engine size, transmission type, power output, and carburetor type (FFS-equipped or non-FFS-equipped). I merged these data with a second dataset from the EPA containing test results for all cars eventually approved for sale in the United States. This dataset contains results from EPA tests of each car's horsepower, fuel consumption performance (MPG) on the combined city and highway cycle, and emissions performance. A third source of data is a set of carburetor repair documents which identify the carburetor manufacturer for a given car model. These documents identify the carburetor manufacturers for 3026 of the 4374 car models in the EPA data. These manufacturers and the counts of automobile models equipped with their carburetors are summarized in Table 1. Finally, US patent data available from the National Bureau of Economic Research (NBER) provide a measure of carburetor firm inventive activity (Hall et al. 2001). These data provide information identifying each patent's assignee as well as information on each patent's importance. I computed annual citation-weighted patent counts for each carburetor manufacturer in patent classes defined by the World Intellectual Property Organization (WIPO)'s International Patent Classification (IPC) system. This system contains distinct classifications for carburetors and for EFI. The dataset that results from these merges is comprised of automobile model observations containing data on the the automobile's performance, characteristics,

[4] For an example of a paper in which carburetor drivability is estimated, see Bresnahan and Yao (1985).

and patenting activity associated with its carburetor. Annual counts of observations are reported in Table 2. This table shows that carburetor manufacturers were identified successfully for most car models over the years of the study.

From 1970 through 1999, the USPTO issued 9506 patents in the IPC classification called "supplying combustion engines in general with combustible mixtures or constituents thereof." Of the those 9506 patents, 1844 are specific to carburetors and 887 are specific to EFI. In carburetors there are 274 assignees. The most prolific assignees are Toyota (137 patents), Honda (83), Nissan (76), Ford (70), and Bosch (62). In EFI, there are 116 assignees, the most prolific of which are Bosch (125 patents), Honda (69), Toyota (58), Nippondenso (46), and Hitachi (45).

## 5 Estimation and Identification

In the analysis below, I test whether firm inventive activity affects the likelihood and the efficacy with which carburetor firms adapt future-technology-derived components for use in their current-technology products. I use firm patenting activity as a measure of firm inventive activity and thereby as a measure of firm experience working with future technologies. Although there are criticisms of using patents as a measure of inventive activity[5], patent data have proved to be valuable tools for measuring innovation. For example, Trajtenberg's (1989) empirical study of Computed Tomography (CT) scan technology finds a strong relationship between citation-weighted patent counts and independent measures of the value of CT innovations. I have chosen patents over one main alternative, firm R&D expenditure data, to measure firm future-technology inventive activity, and have done so for two reasons. First, R&D expenditures typically are reported at aggregated levels in public filings, so it would be impossible to distinguish between EFI-and carburetor-related inventive activity. Second, detailed financial data are not available for most of the carburetor manufacturers in this study. Two of the major carburetor manufacturers, Carter and Holley, were privately held companies, and so financial data on their R&D spending activities are not available. Similarly, Japanese

[5] (Some examples are strategic patenting behavior and unobservability of alternatives to patenting such as trade secrecy protection. For more on issues of patenting and trade secrecy, see the Yale (Levin et al. 1985) and Carnegie Mellon Surveys (Cohen et al. 2000) on intellectual property protection.

firm financial data often are not available and when they are, are subject to different accounting rules, making comparisons with US firms problematic.

5.1 Citation-Weighted Patent Measure

In order to examine empirically the relationship between prior experience with EFI-related invention and the performance of a particular carburetor, I need to measure the EFI-related inventive activity that is associated with a particular car model. To do this, I construct a measure of the number of patents plausibly associated with a given carburetor. I weight this measure to account for heterogeneity in patent quality. Furthermore, I construct the measure so that it may vary over time and so that it accounts for product development lead times. The following paragraphs describe in more detail the construction of this measure.

The first step in constructing the measure is to associate individual patents with automobile carburetors. To do this, I identify the manufacturer of each carburetor in the data. I then associate each carburetor manufacturer with its own patents by conducting string searches for carburetor firm names in the "Assignee" field in the NBER Patent Citation File, manually checking the results for false matches. For example, carburetor patents containing the substring "General Motors" anywhere in the "Assignee" field were associated with General Motors. In the US automobile industry, the employee who invented the technology typically is listed as a patent's inventor, and the employer is listed as the patent's assignee. It is impossible (with available data) to separate such a case from one in which, for instance, an independent inventor has been contracted to perform research for General Motors. The independent inventor will be listed as the patent's inventor, with General Motors listed as the patent's assignee as in the employee-inventor case. The inclusion of patents by independent inventors in the patent measure could then bias this as a measure of firm experience with a given future technology. However, the bias would lead me to underestimate rather than overestimate the effect of firm experience.

Because a carburetor firm's level of inventive activity may be expected to vary over time, I construct measures of firm patenting activity that vary with the model year of each automobile and its associated carburetor in the sample. The level of patenting activity, for example, associated with a 1984 Ford Mustang's Holley carburetor, differs from the level of patenting activity associated with a 1985 Ford Mustang's Holley carburetor.

Product development lead times in the automobile industry are measured in years. Development on an entirely new car may begin seven years before the car is offered to the public. Minor updates may take as little as one year to complete. To account for these long lead times, I assume that the firm inventive activity associated with an individual carburetor takes place in the five years leading up to its availability to the market. So, for instance, the measure of inventive activity for a 1983 Mazda GLC's Hitachi carburetor takes into account patents applied for by (and subsequently granted to) Hitachi from 1978 until 1983. The length of this lead time is limited (that is, I do not include all previous inventive activity) because the "shelf life" of inventive activity is limited. Patents are only included if they were eventually granted by the US Patent and Trademark Office. I use the patent's application date rather than the alternative—the patent's grant date—because the patent's grant date reflects not only the firm's inventive activity, but also factors at work within the USPTO that may not be related to the firm's inventive activity.

To address the criticism that patents are of heterogeneous quality, I construct a measure of each patent's importance, and then weight the patent according to that measure. The measure is the number of times a given patent is cited by other patents applied for (and subsequently granted) in the five years following its application date. The level of inventive activity for an individual carburetor firm j in a given year t is

45

Patentsjt = [1(pat k app for in t-s) (count of cites of pat k in t-s+r )] s=0 kr=1

This measure is calculated for each firm in three patent categories: EFI, carburetors, and semiconductors. The patent measures are summarized by carburetor firm in Table 3.[6]

## 5.2 Hypotheses

[6] For EFI, the IPC category is F02M 51. For carburetors, the IPC categories are F02M 1, F02M 2, F02M 3, F02M 4, F02M 5, F02M 6, F02M 7, F02M 8, F02M 9, F02M 10, F02M 11, F02M 12, F02M 13, F02M 14, F02M 15, F02M 16, F02M 17, F02M 18, and F02M 19. For semiconductors, the IPC categories are H01L andH05K.

I empirically test two hypotheses related to the question of whether absorptive capacity leads to transfers from next-generation technologies to current-generation-technology products. I propose a third hypothesis and present preliminary empirical results that represent a partial test of that hypothesis. First, I predict that firms with more EFI-related inventive activity experience will be better at adapting EFI-derived FFS electronics for use in carburetors. Second, I predict that firms with more EFI-related R&D experience will be more likely to transfer EFI-derived FFS electronics to carburetors. Finally, I suggest that the effects of future-technology-related experience may be limited to technologies sufficiently related to current-technology product to which the components are being adapted.

## 6 Results

The results in this section are organized according to the hypotheses in this paper.

### 6.1 Inventive Activity’s Effect on the Transfer of FFS from EFI to Carbu-retors

Here, I ask whether an increase in prior EFI-related inventive activity increases the impact of EFI-derived technology when it is adapted for use on carburetors. I answer the question by estimating the effect of EFI-and carburetor-related patent measures on a car model’s fuel efficiency (MPG). I interact those patent measures with FFS to determine whether the patent measure on has a different impact on FFS-equipped carburetors. The basic specification with which I test this hypothesis is an OLS regression

$$
\begin{aligned}
MPG_i = {} & \alpha_1 + \beta_1(FFS)_i \\
& + \beta_2(EFIPatents)_i + \beta_3(FFS*EFIPatents)_i \\
& + \beta_4(CarbPatents)_i + \beta_5(FFS*CarbPatents)_i \\
& + \beta_6(ModelYear)_i + \beta_7(FFS*ModelYear)_i \\
& + \beta_8(Tons)_i + \beta_9(FFS*Tons)_i \\
& + \beta_{10}(EngineLiter)_i + \beta_{11}(FFS*EngineLiter)_i + \beta_{12}(AutoTrans)_i + \beta_{13}(FFS*AutoTrans)_i \\
& + \beta_{14}(Horsepower)_i + \beta_{15}(FFS*Horsepower)_i + \varepsilon_i
\end{aligned}
\quad (1)
$$

in which the fuel economy MPG of car model i, defined as the cross product of a make, model, model year, engine, and transmission, is regressed on attributes of the car model and of the carburetor with which it is equipped.  These attributes include the car model's carburetor's manufacturer's citation-weighted count of EFI patents in the five years leading up to the car's production EFIPatents, the interaction between that patent count and the presence of the EFI-derived FFS technology EFIPatents*FFS, a similar measure of carburetor patenting CarburetorPatents and its interaction with FFS, CarburetorPatents*FFS, the car model's year of manufacture ModelYear, and the interaction between that year and the presence of the EFI-derived FFS technology ModelYear*FFS.  I also include variables measuring the car model's weight Tons, engine size EngineLiter, transmission AutoTrans, and power output Horsepower.

The hypothesis predicts that the coefficient estimate on EFIPatents*FFS will be positive, indicating that EFI-related inventive activity improves the efficacy with which the EFI-derived technology, FFS, is applied to carburetors.

The results (see regression 1 in Table 4) show that when EFI-derived FFS electronics are adapted to carburetors by firms with more EFI-related inventive activity expe-rience, FFS has a larger impact on carburetor fuel efficiency.  Specifically, higher levels of EFI patenting activity increase the impact of FFS on carburetor fuel efficiency—about .01 Miles Per Gallon ($\beta 3 = .01$) for each additional carburetor patent citation received.  EFI patenting activity, however, as estimated by the coefficient on EFIPatents, does not have a statistically significant effect on a carburetor's fuel efficiency.

Interestingly, higher levels of carburetor-related inventive activity experience are associated with higher fuel efficiency, about .01 Miles Per Gallon for each additional carburetor patent citation received, but carburetor patenting is not associated with any change in the efficacy with which FFS technology is applied to carburetors—the estimate of EFIPatents*FFS is not statistically significant.  The estimates of the effects of EFIPatents and of EFIPatents*FFS provide indirect evidence that the EFI patent results are not driven by unobserved firm characteristics which could increase product efficiency as well as likelihood to patent—variation in resources would have to affect EFI and carburetor patenting in opposite ways.  These results also suggest that future-technology-related inventive experience is important to the successful adaptation of future-technology-derived components for use current-technology products.

The specification in regression 1 imposes a linear form on patenting's effect on carburetor MPG. It is possible, however, that the relationship is not linear. One might suppose that firms have a finite ability to incorporate innovations, so that marginal improvements to current product diminish as the number of patents increases. Alternatively, one might suppose that there are scale economies associated with firm inventive activity, and so we would expect that an increase in firm inventive experience increases the marginal impact of additional inventive experience. To account for the possibility that patenting experience does not have a linear relationship with MPG, the regression

$$
\begin{aligned}
MPG_i = {} & \alpha_1 + \beta_1(FFS)_i \\
& + \beta_2(EFIPatentsMedium)_i + \beta_3(FFS*EFIPatentsMedium)_i \\
& + \beta_4(EFIPatentsHigh)_i + \beta_5(FFS*EFIPatentsHigh)_i \\
& + \beta_6(CarbPatentsMedium)_i + \beta_7(FFS*CarbPatentsMedium)_i \\
& + \beta_8(CarbPatentsHigh)_i + \beta_9(FFS*CarbPatentsHigh)_i \\
& + \beta_{10}(ModelYear)_i + \beta_{11}(FFS*ModelYear)_i \\
& + \beta_{12}(Tons)_i + \beta_{13}(FFS*Tons)_i \\
& + \beta_{14}(EngineLiter)_i + \beta_{15}(FFS*EngineLiter)_i \\
& + \beta_{16}(AutoTrans)_i + \beta_{17}(FFS*AutoTrans)_i \\
& + \beta_{18}(Horsepower)_i + \beta_{19}(FFS*Horsepower)_i + \varepsilon_i
\end{aligned}
\tag{2}
$$

replaces the linear citation-weighted EFI patent terms in regression 1 with categorical variables indicating Low (2884 carburetors associated with 0 to 33 citation-weighted EFI patents), Medium (988 carburetors associated with 34 to 66 citation-weighted EFI patents), and High (607 carburetors associated with 67-plus citation-weighted EFI patents) patenting levels, with the "Low" patent category being omitted. The citation-weighted carburetor patents terms are also separated into categories, with variables indicating Low (2174 carburetors associated with 0 to 33 citation-weighted carburetor patents), Medium (1465 carburetors associated with 34 to 66 citation-weighted carburetor patents), and High (840 carburetors associated with 67-plus citation-weighted carburetor patents).[7] In similar fashion to regression 1, the patenting categories in regression 2 are interacted with a dummy variable FFS indicating the presence of FFS electronics in the carburetor of car model i. Similar to the expected outcome in regression 1, we expect positive values for the coefficient estimates of FFS*EFIPatentsMedium and FFS*EFIPatentsHigh, indicating that a firm's ability to adapt FFS to carburetors increases with its EFI-related inventive activity.

The results reported in regression 2 in Table 4 show that an increase in EFI patenting activity has no impact on non-FFS-equipped carburetors' MPG (the coefficients on EFIPatentsMedium and EFIPatentsHigh are not significant). The impact of EFI-related patenting on FFS-equipped carburetors is positive and significant, but only at higher levels of patenting. The move from medium to high EFI patenting in FFS-equipped carburetors yields a 1.8 MPG increase in the associated carburetor. As in regression 1, higher levels of carburetor patenting activity are associated with higher carburetor efficiency.

The specifications in regressions 1 and 2 exploit two sources of variation in patenting activity—variation between firms and variation within firms over time. One potential criticism of specifications 1 and 2 is that unobserved (to the researcher) firm characteristics could be acting both on product performance and on patenting activity. Such a condition could lead to incorrect estimates of the effect of patenting on carburetor MPG. Furthermore, it seems likely that some carburetor firms are better at converting inventive activity into product improvements. To account for this possibility, regression 3 in Table 4 includes carburetor firm fixed effects. It is otherwise identical to regression 2. The main change from regression 2 to regression 3.3 is that EFI-derived absorptive capacity how has a statistically significant negative effect on the efficiency of old-fashioned, non-FFS-equipped carburetors. In other words, EFI-derived absorptive capacity is associated with better transfer of technology from EFI to carburetors, but EFI-derived absorptive capacity has a negative association with old-fashioned, non-FFS-

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[7] The citation-weighted EFI patent measure has a mean of 26.1, a max of 107, and a standard deviation of 31.3. The citation-weighted carburetor patent measure has a mean of 44.4, a max of 130, and a standard deviation of 38.2. The results are not sensitive to different categorizations ranging from two categories split at the mean to four categories evenly distributed from zero to the max. With more than four categories, some estimates lose significance because of loss of degrees of freedom

equipped carburetors. Conversely, carburetor-derived absorptive capacity has no relationship with the transfer of FFS technology from EFI to carburetors, but it is associated with improved efficiency of old-fashioned, non-FFS-equipped carburetors. These results seem sensible: Firms are better at the things they spend time and resources on. The key insight, how-ever, is that firms must have created absorptive capacity in the next-generation-technology in order to effectively adapt next-generation technology for use in current-generation-technology products.

A final potential criticism of the specifications in regressions 2, and 3.3 is that the rate of improvement in adapting FFS electronics to carburetors probably was not constant over time. The literature on technological "S"-curves suggests that technologies improve slowly during infancy, improve more quickly during adolescence, and then improve slowly again in old age. If this applies to the trajectory of FFS-equipped carburetor improvement, then the ModelYear and ModelYear*FFS variables, which measure annual improvement in carburetor efficiency and in FFS-equipped carburetor efficiency respectively, are biased. To address these concerns, regression 4 in Table 4 adds model year fixed effects to the specification in regression 3.3. With this addition, effects of patenting are exclusively identified within firms, and the results do not change substantially.

Additional tests of these results are reported in regressions 3.5 through 3.8 in Table 5. These regressions are identical to regressions 3.1 through 3.4 in Table 4, but they are restricted to the population of car models containing FFS electronics to demonstrate that the results in the previous regressions do not result from problems with the FFS interaction specification.

The result in this show that The results do not substantially change. These results show that when firms have more experience with EFI-related inventive activity, their carburetors benefit more from the addition of EFI-related components. This is consistent with the idea that firms' current products may benefit from the addition of future-technology-derived components when firms are better prepared to work with those components—when they have developed absorptive capacity.

6.2 Likelihood of FFS Transfer from EFI to Carburetors

In this section, I ask whether an increase in EFI-related patenting increases the likelihood that a carburetor manufacturer will adapt EFI for use in carburetors. I answer the question by estimating the likelihood that an individual car model will contain FFS electronics, controlling for the relevant attributes of the car model. The base specification (labeled regression 9 here to coincide with results in the tables) is a probit

$$\Pr[FFS = 1]_i = \alpha_1 + \beta_1(EFIPatents)_i + \beta_2(CarbPatents)_i + \beta_3(ModelYear)_i + \beta_4(Weight)_i + \beta\ldots(X)_i + \varepsilon_i \qquad (9)$$

in which the dependent variable is a dummy variable, FFS, indicating the presence of the EFI-derived Feedback Fuel System electronics in car model i 's carburetor. As explanatory variables, I include citation-weighted counts of EFI patents EFIPatents and of carburetor patents CarbPatents. Controls for the car model's attributes include the car's weight Tons, engine size EngineLiters, transmission type AutoTrans, and power output Horsepower.

The results, reported in column 9 in Table 6 show that holding all else constant, EFI-related inventive activity experience (EFIPatents) does not have a significant effect (it is significant only at the 15% level) on likelihood of FFS use in a given car model. Curiously, the point estimate is negative, opposite of what was predicted in hypothesis 1. However, carburetor-related inventive activity experience (CarbPatents) does have a significantly positive effect. These results are puzzling, and further exploration yields information about the relationship between inventive activity experience and likelihood to transfer next-generation technology to current-generation-technology products. Following Trajtenberg (1990), who finds a non-linear relationship between level of patenting and the value of patented inventions, I do not impose a linear form on the absorptive capacity measures in the next regression. Instead, I include citation-weighted patent counts after dividing them into discrete "Low," "Medium," and "High" categories. Similarly, I divide car models into two categories based upon their date of manufacture—1978 through 1985 and 1986 through 1992. Finally, to allow for the possibility that some firm types were more likely to convert EFI-related experience into FFS-equipped carburetor use, I assign each car model to one of four groups based on attributes of the car's carburetor's manufacturer.8 I adjust the standard errors for clustering on these groups of company types.

$$
\begin{aligned}
Pr[FFS = 1]_i = {} & \alpha_1 + \beta_1(EFIPatentsMedium)_i \\
& +\beta_2(EFIPatentsHigh)_i \\
& +\beta_3(CarbPatentsMedium)_i \\
& +\beta_4(CarbPatentsHigh)_i \\
& +\beta_5(YearRange86to92)_i \\
& +\beta_6(Weight)_i + \beta\ .\ .\ .\ (X)_i + \varepsilon_i
\end{aligned}
\qquad (10)
$$

This allows for EFI-and carburetor-related patenting to have nonlinear relationships with the likelihood of FFS use. The results are reported in column 10 in Table 6. These show that a carburetor associated with a medium level of EFI-related inventive activity is more likely to be equipped with FFS than is a carburetor associated with a low level of EFI-related inventive activity. Similarly, a carburetor associated with a high level of EFI-related inventive activity is more likely to be equipped with FFS than is a carburetor associated with a low level of EFI-related inventive activity. However, the relationship between EFI-related inventive activity and likelihood of use of FFS in a carburetor is not linear—a carburetor associated with a high level of EFI-related inventive activity is less likely to be equipped with FFS than is a carburetor associated with a medium level of carburetor EFI-related inventive activity.[8]

The estimate of the effect of carburetor-related inventive activity was positive in the previous specification but, at high patenting levels, is negative in this specification. Here, an increase from low to high carburetor-related inventive activity associated with a given carburetor makes it less likely that that carburetor will be equipped with FFS. This indicates that in the previous probit, the positive relationship at low patenting levels drove the positive estimate in the previous specification.

As a final robustness test, I estimate a probit with carburetor firm random effects instead of adjusting the standard errors for clustering on groups of company types. These

[8] The categories are "Japanese," "American Supplier," "American Carmaker," and "European"

results are reported in column 3.11 in Table 6. The estimates are similar to those in the clustered-standard-errors probit, except that the medium level of carburetor-related patenting is now significantly negative.

In light of the results in the previous section, in which I found that high EFI-related R&D activity yielded larger impact for FFS technology, these results present an interesting puzzle. Perhaps R&D-intensive firms choose to adapt these future technologies less often, but do a better job of it when they do. This distinction between the impact of R&D experience on the firm's ability to discern opportunities and on the firm's ability to exploit new technologies is a topic for later research.

6.3 Relatedness of Technologies: Preliminary Results

The results in this paper support the hypotheses that experience working with next-generation technology makes the transfer of next-generation-derived components to current-generation products both more likely and better. One might reasonably ask whether experience working with any future technology increases the likelihood and value of these intergenerational technology transfers. My preliminary attempt to address this question is to identify a technology— semiconductors—that is plausibly but distantly related to FFS electronics. Although semi-conductor technology is reasonably related to FFS technology (FFS electronics are based on semiconductors, many of which were custom made for automotive applications), it is more distantly related than is EFI. Thus I expect that the impact of semiconductor-related inventive activity experience on the application of FFS to carburetors will be smaller than is the impact of EFI-related inventive activity experience. To address this question, in regressions 3.12 through 3.15 in Table 7 I include variables that measure the level of semiconductor patenting associated with each car model.

The regression results show that semiconductor-related absorptive capacity has a significant impact on carburetor performance. In regression 3.12 in Table 7, semiconductor patenting positively affects old-fashioned, non-FFS-equipped carburetor MPG—the estimate of the ChipPatents coefficient is .012. However, semiconductor patenting negatively affects the MPG of FFS-equipped carburetors. These results hold when the semiconductor patenting variable is discretized and year and carburetor company fixed effects are included (regression 3.13 in Table 7), at least at the medium level of semiconductor patenting.

The carburetor firm patent counts in Table 3 show that one firm, Hitachi, was an EFI-patenting outlier. To account for the possibility that the inclusion of Hitachi's semiconductor patents is driving the results, I exclude Hitachi from regression 3.14 in Table 7. I reassign the bin values for "Low," "Medium," and "High" semiconductor patenting because Hitachi was the sole occupant of the "High" category in regressions 3.12 and 3.13. The previously significant effects of semiconductor patenting experience no longer have a significant effect on old-fashioned-or FFS-equipped-carburetor performance. One possible interpretation of these results is that R&D experience must be sufficiently closely related to the technologies from which firms will adapt components for use in their current products. This question will be addressed in future research.

## 7 Discussion and Conclusion

The psychological and organizational mechanisms that lead to absorptive capacity are well understood. But we are less sure of what it means for a product to "absorb" a new technology. In other work, I showed that components from next-generation technologies can be adapted for use in current-generation-technology products in a way that increases the current-generation-technology product's performance. I also found a result suggestive of the idea that firms that made rather than bought a new technology, EFI, were able to wring more performance out of FFS when it was applied to carburetors. In this paper, I empirically test two hypotheses related to the question of whether absorptive capacity leads to transfers from next-generation technologies to current-generation-technology products. I also propose that absorptive capacity's effects are limited in scope to technologies sufficiently related to the transfer.

I find that absorptive capacity related to the next generation of technology, as measured by patenting activity, increases the likelihood that a firm will transfer next-generation technology to current-generation-technology products. I also find that this absorptive capacity increases the efficiency with which a next-generation-technology is transferred to the current-generation-technology products. Finally, I find evidence that suggests that those inventive activities must be sufficiently closely related to the current-generation-technology products for them to impact absorption of the next-generation-technology component.

Table 1: Automobile Model Carburetor Observations by Carburetor Manufacturer

| Carburetor Manufacturer | N in Manuals & in EPA Data | Percent |
|---|---|---|
| Aisan | 259 | 8.6 |
| Carter / ACF | 750 | 24.8 |
| Ford / Motorcraft | 129 | 4.3 |
| Hitachi | 321 | 10.6 |
| Holley / Colt | 94 | 3.1 |
| Weber | 215 | 7.1 |
| Keihin | 140 | 4.6 |
| Mikuni | 205 | 6.8 |
| Nikki | 6 | 0.2 |
| GM / Rochester | 907 | 30.0 |
| Total | 3,026 | 100.0 |

Table 2: Automobile Model Observations by Model Year

| Model Year | N in EPA Data | N in EPA & in Patent Data |
|---|---|---|
| 1979 | 438 | 228 |
| 1980 | 564 | 370 |
| 1981 | 542 | 415 |
| 1982 | 633 | 480 |
| 1983 | 637 | 453 |
| 1984 | 378 | 279 |
| 1985 | 448 | 330 |
| 1986 | 322 | 217 |
| 1987 | 207 | 140 |
| 1988 | 96 | 64 |
| 1989 | 59 | 31 |
| 1990 | 24 | 12 |
| 1991 | 15 | 3 |
| 1992 | 11 | 4 |
| Total | 4374 | 3026 |

Table 3: Patents By Carburetor Manufacturer and Category, Summed Over Years

| Carburetor Manufacturer | EFI Category | Carburetor Category | Semiconductor Category |
|---|---|---|---|
| Aisan | 119 | 358 | 131 |
| Carter / ACF | 0 | 306 | 0 |
| Ford / Motorcraft | 125 | 549 | 2406 |
| Hitachi | 542 | 662 | 25,751 |
| Holley / Colt | 78 | 211 | 0 |
| Weber | 114 | 117 | 6 |

| | | | |
|---|---|---|---|
| Keihin | 0 | 3 | 0 |
| Mikuni | 21 | 111 | 0 |
| Nikki | 0 | 0 | 0 |
| GM / Rochester | 860 | 860† | 1780 |

1978-1992 annual counts summed. Annual counts include cita-tion weighted patents in five-year window of interest.
†GM's EFI patents coincidentally sum to the same number as do its carburetor patents.

Table 4: OLS: Patenting's Effect on Efficacy of FFS Spillover

| Dep. Var.: MPG | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| FFS | 30.134 | -4.832 | 49.072 | 10.036 |
| | (159.188) | (145.253) | (146.094) | (1.872)** |
| EFIPatents | -0.001 | | | |
| | (0.004) | | | |
| FFS*EFIPatents | 0.010 | | | |
| | (0.006)+ | | | |
| EFIPatentsMedium | -0.283 | -0.751 | -1.199 | |
| | (0.290) | (0.282)** | (0.303)** | |
| FFS*EFIPatentsMedium | 0.193 | 0.090 | 1.011 | |
| | (0.426) | (0.417) | (0.458)* | |
| EFIPatentsHigh | -0.451 | -1.332 | -0.935 | |
| | (0.398) | (0.534)* | (0.641) | |
| FFS*EFIPatentsHigh | 1.801 | 2.019 | 2.125 | |
| | (0.540)** | (0.509)** | (0.597)** | |
| CarbPatents | 0.014 | | | |
| | (0.003)** | | | |
| FFS*CarbPatents | -0.006 | | | |
| | (0.005) | | | |
| CarbPatentsMedium | 0.793 | 1.256 | 0.706 | |
| | (0.197)** | (0.231)** | (0.245)** | |
| FFS*CarbPatentsMedium | -0.260 | -0.589 | -0.387 | |
| | (0.310) | (0.311)+ | (0.324) | |
| CarbPatentsHigh | 1.674 | 1.657 | 1.812 | |
| | (0.280)** | (0.431)** | (0.445)** | |
| FFS*CarbPatentsHigh | -0.138 | 0.088 | -0.449 | |
| | (0.501) | (0.519) | (0.555) | |
| ModelYear | 0.603 | 0.621 | 0.654 | |
| | (0.055)** | (0.050)** | (0.048)** | |
| FFS*ModelYear | -0.010 | 0.008 | -0.020 | |
| | (0.080) | (0.073) | (0.074) | |
| Tons | -9.059 | -9.050 | -8.136 | -8.452 |
| | (0.387)** | (0.394)** | (0.379)** | (0.379)** |
| FFS*Tons | -7.029 | -7.097 | -6.173 | -5.341 |
| | (0.684)** | (0.686)** | (0.654)** | (0.653)** |
| EngineLiters | -0.447 | -0.502 | -0.063 | -0.022 |

| | | | | |
|---|---|---|---|---|
| | (0.171)** | (0.171)** | (0.177) | (0.177) |
| FFS*EngineLiters | 1.681 | 1.747 | 1.599 | 1.454 |
| | (0.256)** | (0.256)** | (0.245)** | (0.244)** |
| AutoTrans | -1.453 | -1.432 | -1.326 | -1.290 |
| | (0.151)** | (0.152)** | (0.143)** | (0.141)** |
| FFS*AutoTrans | 0.282 | 0.235 | 0.104 | -0.098 |
| | (0.241) | (0.242) | (0.228) | (0.226) |
| Horsepower | -0.043 | -0.040 | -0.045 | -0.041 |
| | (0.005)** | (0.006)** | (0.006)** | (0.005)** |
| FFS*Horsepower | -0.030 | -0.036 | -0.039 | -0.044 |
| | (0.008)** | (0.008)** | (0.008)** | (0.008)** |
| Fixed Effects | | CarbFirm<br>ModelYear | CarbFirm | |
| Constant | -1,149.343 | -1,185.227 | -1,253.961 | 39.959 |
| | (107.962)** | (99.293)** | (94.675)** | (0.521)** |
| Observations | 3025 | 3025 | 3025 | 3025 |
| R-squared | 0.84157 | 0.84293 | 0.63546 | 0.65016 |

Robust standard errors in parentheses; + significant at 10%; * significant at 5%; ** significant at 1%.

Table 5: OLS: Patenting's Effect on Efficacy of Carburetor MPG (Restricted to Cars Equipped with FFS)

Dep. Var.: MPG (5) (6) (7) (8)
ModelYear 0.593 0.629 0.453
EFIPatents (0.064)** 0.009 (0.058)** (0.066)**
EFIPatentsMedium (0.005)+ -0.089 0.533 1.831
EFIPatentsHigh CarbPatents 0.008 (0.340) 1.350 (0.397)** (0.503) 2.324 (0.803)** (0.549)** 4.084 (0.889)**
CarbPatentsMedium (0.004)+ 0.533 -0.051 -0.615
CarbPatentsHigh Tons -16.088 (0.261)* 1.536 (0.451)** -16.147 (0.338) 1.215 (0.530)* -14.393 (0.372)+ 1.200 (0.558)* -13.987
EngineLiters AutoTrans (0.614)** 1.234 (0.207)** -1.171 (0.611)** 1.246 (0.207)** -1.197 (0.607)** 1.589 (0.218)** -1.386 (0.600)** 1.454 (0.219)** -1.548
Horsepower Fixed Effects (0.204)** -0.073 (0.007)** (0.204)** -0.076 (0.007)** (0.197)** -0.084 (0.007)** CarbFirm (0.195)** -0.083 (0.007)** CarbFirm
ModelYear

| | | | | |
|---|---|---|---|---|
| Constant | -1,119.208 | -1,190.059 | -843.571 | 47.542 |
| | (127.438)** | (115.274)** | (131.496)** | (2.193)** |
| Observations | 1237 | 1237 | 1237 | 1237 |
| R-squared | 0.82708 | 0.82926 | 0.58898 | 0.61101 |

Robust standard errors in parentheses; + significant at 10%; * significant at 5%; ** significant at 1%.

Table 6: Probit: Patenting's Effect on Likelihood of FFS Use on Given Carburetor

FFS=1 (9†) (10††) (11†††)
EFIPatents -0.002
EFIPatentsMedium (0.001) 1.329 1.541
EFIPatentsHigh CarbPatents 0.008 (0.206)** 0.634 (0.185)** (0.166)** 0.944 (0.118)**
CarbPatentsMedium (0.001)** -0.397 -0.700
CarbPatentsHigh ModelYear 0.489 (0.528) -1.051 (0.529)* (0.073)** -1.195 (0.141)**
YearRange86to92 Tons (0.021)** -2.319 1.031 (0.611)+ -1.585 1.061 (0.086)** -1.711
EngineLiters AutoTrans (0.165)** 0.764 (0.064)** 0.302 (0.346)** 0.457 (0.143)** 0.189 (0.172)** 0.326 (0.065)** 0.228
Horsepower Constant (0.058)** -0.013 (0.002)** -967.722 (0.198) -0.008 (0.002)** 1.811 (0.055)** -0.008 (0.002)** 2.707
(42.053)** (0.743)* (0.190)**
Observations 3025 3025 3025

†Standard errors in parentheses; + significant at 10%; * significant at 5%; ** significant at 1%.
††Standard errors adjusted for clustering on carburetor com-pany type;
†††Includes carburetor firm random effects;
Table 7: OLS: Patenting's Effect on Efficacy of FFS Spillover (Semiconductor Patenting)

Dep. Var.: MPG (11) (12) (13)
FFS -96.843 11.126 11.777
(162.965) ( 1.962)** (1.974)**
EFIPatents -0.004
(0.004)
FFS*EFIPatents 0.015
(0.006)*
EFIPatentsMedium -1.159 -1.137
(0.305)** (0.299)**
FFS*EFIPatentsMedium 1.196 2.078
(0.499)* (0.722)**
EFIPatentsHigh -0.385 -1.046
(0.656) (0.776)
FFS*EFIPatentsHigh 1.708 3.012
(0.597)** (0.866)**
CarbPatents 0.012
(0.003)**
FFS*CarbPatents -0.001
(0.005)
CarbPatentsMedium 0.204 0.449
(0.260) (0.239)+
FFS*CarbPatentsMedium 0.620 0.531

| | | | | | | |
|---|---|---|---|---|---|---|
| | | (0.373)+ | | (0.348) | | |
| CarbPatentsHigh | | | | 1.835 | 2.734 | |
| | | (0.450)** | | (0.629)** | | |
| FFS*CarbPatentsHigh | | | | | -0.147 | -0.873 |
| | | (0.565) | | (0.873) | | |
| ChipPatents | | 0.001 | | | | |
| | (0.000)** | | | | | |
| FFS*ChipPatents | | | -0.002 | | | |
| | (0.000)** | | | | | |
| ChipPatentsMedium | | | | 4.367 | 0.000 | |
| | | (1.557)** | | (0.000) | | |
| FFS*ChipPatentsMedium | | | | | -3.028 | -0.709 |
| | | (0.464)** | | (0.665) | | |
| ChipPatentsHigh | | | | 0.000 | 1.507 | |
| | | (0.000) | | (2.408) | | |
| FFS*ChipPatentsHigh | | | | | 2.576 | -1.052 |
| | | (1.691) | | (2.536) | | |
| ModelYear | | 0.597 | | | | |
| | (0.054)** | | | | | |
| FFS*ModelYear | | | 0.054 | | | |
| | (0.082) | | | | | |
| Fixed Effects | | | CarbFirm | | CarbFirm | |
| | | ModelYear | | ModelYear | | |
| Constant | | -1,138.185 | | 39.148 | | 38.189 |
| | (107.620)** | | (0.550)** | | (0.533)** | |
| Observations | | 3025 | 3025 | 2704 | | |
| R-squared | | 0.84280 | | 0.65585 | | 0.68337 |

Robust standard errors in parentheses; + significant at 10%; * significant at 5%; ** significant at 1%.
Variables Tons, EngineLiters, AutoTrans, and Horsepower included in regressions but not reported for space considerations.

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