Extraordinary Efficiency Growth in Response to New Technology Entries: The Carburetor's "Last Gasp" *

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Abstract

Technologies often experience a period of extraordinary improvement or a "last gasp" before being superseded by new technologies. The standard explanation for this last gasp is that adherents of threatened technologies try harder to improve their technology after the threat from a new technology materializes. Although this phenomenon should inform the study of technological transitions in general and firms' technology policy decisions in particular, the "trying harder" explanation has not been tested against alternative explanations. In this paper, I develop and test two new explanations for last gasps. The first, a selection effect, is that new technologies force old technologies out of inefficient applications, making them appear to be more efficient on average. The second is that entrant technologies sometimes introduce efficiency-enhancing component technologies that may be "spilled over" to incumbent technologies. To test these and the trying harder explanation, I use two datasets. First, I construct an original dataset covering the last gasp of carburetor efficiency which occurred during the 1980s when a substitute technology, Electronic Fuel Injection (EFI), entered the market. The second is data from the US Patent and Trademark Office. I find that the carburetor's last gasp was caused by the selection effect and by the spillover of electronic control technology from Electronic Fuel Injection to carburetors. Significantly, however, only those carburetor firms that also manufactured EFI were able to capture the benefits of these spillovers, a result consistent with the "Absorptive Capacity" theory. Some carburetors from threatened firms experienced an increase in efficiency, but the interpretation of this result is ambiguous.

1 Introduction

Technologies often seem to improve when they are threatened with replacement by a new technology. Economic historians and innovation scholars have noted this pattern in sailing ships (Gilfillan 1935a; Harley 1971), alkali (Rothwell and Zegveld 1985), typesetters (Tripsas 2001), and ice harvesting (Utterback 1994), among other technologies. In generic terms, the phenomenon can be thought of as an extraordinary improvement in an incumbent technology in the face of a threat from an entrant replacement technology. The phenomenon, in various forms, has been called the "sailing ships phenomenon" and the "last gasp" of a technology (Tripsas 2001).

The common explanation for last gasps is that adherents—producers and users—of old technologies "try harder" to find efficiency improvements when their technology is threatened by a new technology. Nathan Rosenberg summarizes the idea concisely:

> . . . [I]nnovations often appear to induce vigorous and imaginative responses on the part of industries for which they are providing close substitutes. . . . The imminent threat to a firm's profit margins which are presented by the rise of a new competing technology seems often in history to have served as a more effective agent in generating improvements in efficiency than the more diffuse pressures of intra-industry competition. (1976, 205)

Utterback makes a similar observation in his book on innovation, in which he describes a number of cases of last gasps. In his analysis of these examples, he concludes that firms with a stake in the incumbent technology "do not always sit back and watch their markets disappear. Most fight back" (1994, 159).

While "trying harder" has both a long intellectual history and an intuitive appeal to anyone who has ever risen to meet a challenge, this paper will argue that it is not the only reason for which extraordinary gains might be observed when a technology is faced with competition from a new substitute. I offer two alternative explanations for last gasps which I believe to be novel to this paper. The first is that last-gasp efficiency improvements may not be caused by technological improvements at all. Rather, they result from a phenomenon in which the market is divided by the entrant and incumbent technologies. This selection mechanism allows technologies to be used in applications to which they are best suited, increasing efficiency and leaving the old technology in the most efficient portion of the market. The second alternative explanation is that that components from entrant technologies may "spill over" to incumbent technologies, and thus improve the incumbent. In other words, new technologies may contain components that can be applied to old technologies and thus increase the old technologies' performance.

This paper examines the role of these three ostensible mechanisms in explaining the changes in automobile carburetor efficiency during the period in which Electronic Fuel Injection (EFI) entered and displaced carburetors from the automobile market in the United States. Carburetors exhibited a last gasp of efficiency growth in this period, and using detailed data on automobile characteristics and fuel efficiency, I find evidence that all three phenomena were at work. In particular, I find, in support of the substitution explanation, that carburetors persisted in a subset of cars whose other characteristics, primarily weight and horsepower, led to greater fuel efficiency than that found in the growing subset of cars that were equipped with EFI. This effect, which I call the "selection" effect, explains much of the last gasp observed across vehicles. Looking at differences in fuel efficiency, however, reveals strong evidence of efficiency–increasing technological spillovers from EFI to carburetors. Finally, there is evidence that some carburetors built by firms most threatened by the entrance of EFI experienced an unexplained jump in efficiency growth. An examination of these firms' patenting behavior does not indicate the presence of a change in innovative activity during this time.

This paper makes three contributions to the literature. The first is to add automobile carburetors as another example of last gasps. The second is to introduce, as explanations for last gasps, selection and spillovers. The third is to assess the relative importance of different (non–mutually–exclusive) explanations for last gasps, an endeavor that has not been possible previously because of a lack of sufficiently detailed data.

On a more general level, understanding the mechanisms behind last gasps sheds light on broader questions concerning innovation. Because we think that marginal improvements become more difficult as technologies age, the existence of last gasps suggests unexpected forces at work in technological innovation and in firm performance. Also, getting the explanation right for last gasps is important if we hope to understand how competition affects technological innovation, how firms work, how transitions from one technological standard to the next happen, and whether firms' new technology sourcing decisions can affect the current technology's development. At this level, the question of what causes last gasps is of interest to innovation scholars, organizational theorists, economic historians, and managers.

This paper proceeds as follows. In section 2, I discuss my proposed explanations for last gasps in the context of the literature. In section 3, I describe the setting in which carburetors were replaced by an entrant technology. In section 4, I describe the data I use to test explanations for the carburetor's last gasp. Section 5 describes empirical analysis based on the EPA data, and Section 6 describes empirical analysis based on the patent data. Section 7 is a discussion and conclusion.

2 Theoretical Discussion and Literature Review

This section reviews the existing literature that has concerned itself with last gasps, particularly the last gasp of the sailing ship. In this literature, a last gasp has been defined as an extraordinary improvement in a technology or in its performance. This section considers how to define a last gasp in the specific context of automobile carburetors. Finally, this section elaborates in more detail the three explanations for last gasps that are considered in the paper.

2.1 The Last Gasp

The earliest work on last gasps was done by economic historians studying sailing ship efficiency improvements in the face of competition from steam-powered ships. Lewis Rex Miller (1927) and Abbott Payson Usher (1928) studied data collected from English state shipping papers. Their studies showed that sailing ship productivity had grown over time. Usher observed anomalously large growth in sailing ship productivity in the late 19th century, and attributed it to technological innovation (477). In subsequent work, Gilfillan (1935a; 1935b) claimed that sailing ships adherents increased the pace of sailing ship technological improvement as a response to the introduction of steam power. Douglass North, however, proposed that the increases in productivity of sailing ships resulted from market organization changes rather than from technological improvements (1958; 1968). Knick Harley (1988) returned to the earlier interpretation, revisiting North's data and showing that the large improvements in shipping efficiency occurred during the height of competition between sails and steam, and seemed to be attributable to technological improvements. Subsequent work in last gasps has been strongly informed by the sailing ships research. The most notable examples are James Utterback, who cites last gasps in ice production (1994), and Rebecca Henderson, who describes the phenomenon of optical photo–lithography surviving longer than predicted after the entrance of x–ray photo–lithography (1995).

2.2 What Is a Last Gasp?

One definition of last gasps comes from John Howells. He suggests that a last gasp is "the acceleration of innovation in the old technology in response to the threat from the new" (2002). But restricting attention to "innovation" neglects the possibility that efficiency improvements in threatened technologies occur for reasons other than technological improvement. In this study, I accommodate this concern and define the last gasp as an extraordinary *efficiency* improvement in a technology immediately preceding the death of the technology. As an empirical matter, this requires the establishment of a counterfactual against which to compare the incumbent technology's performance. Possible counterfactuals include incumbent performance before the entrant arrives, zero performance growth, and the entrant's performance. The counterfactual that best captures the spirit of the existing literature is the incumbent technology's performance before the entrant's arrival. Under this definition, a last gasp is a positive change in the rate of efficiency improvement after the arrival of a competitor technology which ultimately replaces the incumbent technology. This is the definition I use in this paper.[1]

2.3 Explanations

The most commonly cited explanation for last gasps is that adherents of an incumbent technology redouble their efforts to innovate when their technology is threatened by an entering substitute technology (Rosenberg 1976; Utterback 1994).

Any competing explanation for last gasps must meet at least one basic criterion. That criterion is that the mechanism which causes a performance increase in the incumbent must be triggered by the appearance of the entrant technology. That is, the performance increase observed in the incumbent technology must be non-random and plausibly be caused by the introduction of the new technology. A random shock that increases the efficiency of an incumbent technology may be interesting as an anecdote, but its application is limited. In this paper, I consider three explanations for last gasps, and those three explanations meet this basic criterion.

2.3.1 Trying Harder

The trying harder explanation has strong intuitive appeal because it describes the familiar human behavior of rising to meet a challenge. When faced with a threat, especially a potentially fatal one, organisms often increase their performance to avoid being selected out of the population.

In the context of evolutionary biology, this phenomenon was identified and termed the "Red Queen" effect by biologist Leigh Van Valen in 1973. The Red Queen takes its name from an episode in Lewis Carroll's *Through the Looking Glass* in which the Red Queen tells Alice "in this place it takes all the running you can do, to keep in the same place." Advantageous mutation in one organism forces competitor organisms to evolve at a faster rate or to be selected out of the population.

[1] Because the "death" of an incumbent technology is required under the definition I use in this paper, it is only possible to say after the fact that we have observed a last gasp. Therefore, my analysis requires a retrospective view and is conditioned upon an ultimate victory by the entrant technology and departure of the incumbent from the market. One reason to examine last gasps in retrospect is that it is impossible to predict when an entrant technology will be adopted and completely displace the incumbent technology.

Organizational theorists and macroeconomists have ascribed, with some success, this dynamic to economic competition among firms and among economies (Barnett and Hansen 1996; Barnett and Sorensen 1999; Krugman 1979). However, the Red Queen effect can apply to technological competition only if adherents to the old technology can't or won't switch to an obviously better alternative technology, and must therefore improve the old technology in order to survive. In the context of evolutionary biology, one species cannot will itself to develop the traits of another. But firms are more able to choose to switch to an alternative technology. In light of this, Howells (2002) points out that for trying harder to be a credible explanation for a given last gasp, there needs to be some convincing reason for which firms would try harder rather than exit or switch to a different technology. He asserts that "exit" and "switch" are therefore far more likely real-world responses than is trying harder.

Firms might cling to technologies because they believe their technology eventually will win. The outcomes of technology races are almost always uncertain, which makes it is impossible to predict with complete accuracy which technology eventually will win and which one will lose. Where exit costs are high, a firm that has bet on the wrong horse may find itself in a position in which its only choice is to continue to develop a technology that is probably doomed. Another way to explain why firms might stay with a losing technology was offered by Joseph Schumpeter, who suggested devotion to, and improvement of, sailing ships was a result of "extra rational preference" for the old technology (1939, 369). This is a difficult hypothesis to refute.

Quite apart from the issue of why a firm would remain devoted to a losing technology is the question of how a firm could squeeze extraordinary improvements from an old technology. One of the principal difficulties with the trying harder explanation is that it assumes the presence of technological or organizational "slack" that can be exploited once a competitor technology materializes. Such slack could take the form of unimplemented know–how, underutilization of human capital, or inefficient organizational form. This is a problematic element of the trying harder hypothesis because the pressures of market competition typically eliminate such slack, and many of the last gasps cited in the literature occurred in technologies that existed in competitive markets before the entrance of a competitor technology. Sailing ship cargo hauls, for instance, were bid upon in auctions. Knick Harley writes:

> There can be little doubt that the shipping industry in the late nineteenth century closely approximated the economist's model of perfect competition. There were very large numbers of participants in the market, and entry was open to anyone with $15,000 to $20,000 to invest in a ship.... The largest fleets consisted of just over 100 ships each.... The majority of owners owned only one or two ships. Under

> these conditions, although liner conferences might have had some control over some line freights, it seems impossible that tramp freights could have been anything but competitively determined. The existence of an auction market for shipping service—the Baltic Exchange—and of professional brokers, both characteristic of a competitive market, reinforces this belief. (1971, 225)

Other technologies cited as having had last gasps, including, in this paper, carburetors, were in competitive markets before the entrance of the new technology.

In conclusion, trying harder is most likely to be a contributing element to last gasps in markets in which there are high exit and switching costs associated with the old technology, acting in concert with imperfect competition before the entrant technology arrives.

2.3.2 Selection

The selection hypothesis arises because new technologies generally make their way into new applications gradually and because the pattern of diffusion is likely not to be random. Instead, when a substitute technology arrives on the market, if it doesn't displace the old technology immediately, efficiency gains for the old technology will result from a change in application rather than from actual technological innovation. The new technology is likely to appear first in applications in which its efficiency impact, or more precisely its comparative advantage, is largest. If these applications are those in which the old technology has not only an absolute disadvantage, but also a comparative disadvantage, then the average efficiency of the old technology in its remaining applications will be higher than it was before the arrival of the new technology. Translating this to the carburetor example in this paper, if EFI systems found their first application in heavier or more powerful cars, then carburetors would have been left in lighter, less powerful, and consequently, more fuel–efficient cars. The average fuel efficiency of the carbureted cars would increase over time even if there were no technological innovation in carburetors. The change in fuel efficiency attributable to the change in the characteristics of the population of carbureted car which are unrelated to the fuel delivery system (carburetors or EFI) is what I mean by the selection effect.

Because new technologies often are expensive and unproven, they enter the product space gradually. With time, the new technology displaces the old technology from the applications to which the old technology is most poorly suited. This displacement is more likely to occur where the efficiency impact from the new technology is largest. This is on the most inefficient applications of the new technology types. So the old technology appears to improve because it is being used in more appropriate applications, which also happen to be the most efficient applications. In this paper, I refer to this mechanism as "fit" and "selection."

Though it wasn't explicitly identified as a cause of last gasps, the idea of selection made its way into Knick Harley's 1971 paper on the last gasp of sailing ships. In his paper, he shows that steamships gradually displaced sailing ships from markets in which steam held advantages. The first routes on which this happened were short-haul passenger and cargo routes along the British coast and across the Irish Sea (Harley 1971, 222). On short routes, steamships held an advantage in predictable arrival times, lower sensitivity to weather, and maneuverability. At first, steamships were disadvantaged on long routes because they were slower than sailing ships and had to devote much of their cargo capacity to the carriage of coal for fuel. As steamship technology was developed, speed and fuel efficiency increased. This allowed for a gradual displacement of sailing ships from longer routes.

Implicit in Harley's analysis is the point that the entrant technology displaced the incumbent technology from some applications. One can easily see how this could have increased the aggregate efficiency of the incumbent technology in use because it was used for applications in which it maintained a comparative advantage. So, even with static incumbent technology, the application of that technology to more efficient uses (forced by the entrance of the new technology) can create an apparent increase in the incumbent's efficiency.

2.3.3 Spillovers

The selection explanation proposes that incumbent technology efficiency can improve even without technological change. In this section, I propose that an entrant technology may directly speed the process of technological improvement in an incumbent technology if there are components from the entrant technology that "spill over" to the incumbent technology, thus improving the performance of the incumbent. Most technologies can be decomposed into a number of component parts. Often, for a new technology to work, a number of new component technologies must be developed. Once a new component has been developed and perfected for use in the entrant technology, it may be possible to adapt it to use in other technologies, including in an incumbent technology.

Scholars have recognized that interaction among technological components may have an effect on innovation. A stream of research devoted to modularity in technological innovation has examined how component technologies interact and how they affect firm performance (Baldwin and Clark 2000, e.g.,). Alwyn Young (1993) proposes a model of endogenous innovation in which final goods are composed of subsets of the population of intermediate goods. New intermediate goods make the old final goods more efficient for a time until ultimately they are displaced by newer, more efficient final goods (1993, 777). The idea of "blending" new and old technologies to obtain some final product with desirable efficiency properties appears in the development literature, too (Rosenberg 1988, 16).

In this paper, I argue that one way in which technologies combine is that component technologies systematically spill over from entrant to incumbent technologies. For this to be considered as a plausible explanation for last gasps, it must be the case that some component technologies introduced as part of entrant technologies were unavailable or too costly before the appearance of the entrant. The introduction of the entrant is a necessary condition of the introduction of the new component technology. In the case of sailing ships, iron hulls made their way from steamships to sailing ships. In the case at hand, certain electronic components were developed for use in EFI systems, but subsequently they were adapted for use in carburetors.

I remain agnostic as to the reasons for which the spillover technologies were infeasible or unavailable before the appearance of the entrant. Most likely, it is that the new spillover technology represents a negative net–present–value project as a component of the incumbent because the incumbent technology is expected to be close to the end of its development potential. But it represents a positive net–present–value project as a component of the entrant technology, and the entrant technology, in its infancy, promises more growth and economic returns.

3 Carburetor Technology and the Industry

The goal of this paper is to investigate the extent to which selection, spillovers, and firms' trying harder contribute to the last gasp of efficiency growth that took place at the end of the automobile carburetor's life during the 1980s. The competition between carburetors and EFI is an attractive candidate for study because carburetors represent an important component in a very large industry. Furthermore, the battle between incumbent and entrant was clearly defined because they were direct substitutes for one another.

3.1 Carburetor Technology

Automobile carburetors serve the purpose of mixing gasoline and air in a ratio that can be burned efficiently by the car's engine. They use simple suction to draw gasoline into the stream of air entering the engine. Because they are "dumb" mechanical devices, carburetors do not provide the optimal mixture of gasoline and air under all possible operating conditions, leading to non-optimal fuel economy and emissions levels.

Carburetors were the standard technology for mixing gasoline and air from the invention of the automobile in the late 1800s through the early 1980s. Most cars and trucks were equipped with carburetors during that period. In the 1960s and 1970s, increasing oil prices and a growing awareness of air pollution moved US policymakers to regulate automobile fuel consumption and airborne pollutant emissions. The regulations were phased in over a period from 1968 through 1990. In response to those regulations to improve fuel efficiency and air emissions performance, automakers developed technology so that they could meet consumer expectations and satisfy regulations. By the end of the 1970s, carburetor technology seemed to be pushed to the limit of its ability to achieve high fuel economy and accommodate emissions control equipment.

In 1980, an alternative to carburetors called Electronic Fuel Injection (EFI) was offered for the first time on mass-produced automobiles. One important feature of EFI was the use of electronic controls that gauged the performance of the automobile engine and made changes to its operating parameters in real time to adjust to changing conditions. EFI used an on-board computer system to accomplish this task.[2] EFI also used tiny, electronically-controlled valves to admit gasoline under high pressure into the engine. This allowed precise control of the ratio of fuel to air in the mixture the engine burned to make power. This increased precision allowed automakers to use more advanced emissions control devices and it gave cars better fuel economy.

3.2 The transition from carburetors to EFI

The transition from carburetors to EFI as the automobile industry standard was a gradual one. Figure 1 on the following page plots counts of car models offered for sale containing carburetors and EFI over time. This plot shows that a there was a ten-year transition period from carburetors to EFI.

Although EFI systems were superior to carburetors, they didn't immediately replace carburetors. The gradual transition was caused by at least three factors. The first is that EFI systems were more expensive than were carburetors. Early EFI systems cost $600 more per unit than carburetors. As a result, the early EFI systems were found on luxury and performance cars, in whose sales price a $600 increase in cost could be absorbed. Furthermore, the two technologies were effectively identical from the perspective of most car owners. Though the performance advantages of EFI were recognized by performance car enthusiasts, EFI was not a feature for which most customers were willing to pay a premium. The most important reason for equipping cars with EFI was to help cars achieve better fuel mileage performance

[2]During World War II, the German firm Bosch invented mechanical fuel injection (MFI) for use on German fighter planes. This technology was further developed after the war, and it eventually found its way into high-end and racing automobiles. It used a complex mechanical pump to deliver pulses of gasoline through nozzles into each cylinder in the engine. Even apart from the electronics, EFI was very different from MFI. In other words, EFI was not just MFI with electronics attached. Typical EFI systems contained fuel injectors receiving gasoline from a common pressurized "fuel rail." These injectors contained fuel valves that were opened and closed by solenoids, or electromagnetic switches. The opening and closing of these solenoids was controlled by a computer. Because MFI's application was limited to a few high-end automobiles, and it is (literally, here) an historical footnote, I don't include it in the analysis in this paper.

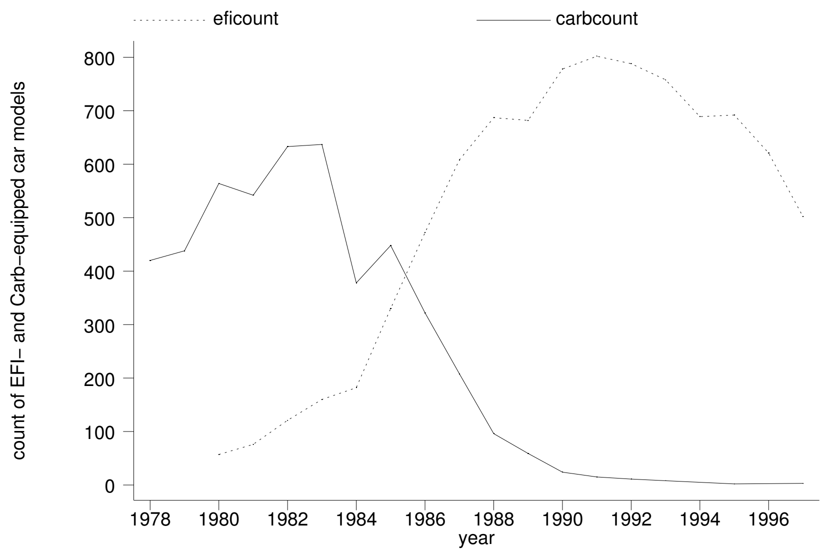

Figure 1: Count of Annual EFI and Carburetor Usage

and to allow the use of more sophisticated emissions control technologies.

The second reason for the slow transition to EFI was quality and service issues. The early EFI systems were less reliable than were carburetors. Automakers had little experience in adapting electronics to the harsh environment of the automobile, so the car's engine control computer, or "brain," was prone to damage from electromagnetic interference, vibration, heat, and moisture. When cars broke down because of EFI system failures, the technology was so new that many mechanics and technicians couldn't fix them.

The third reason for the slow transition from carburetors to EFI was that EFI did not decisively win the technology horserace immediately. As proof of this, even in the early 1980s, industry observers were not sure that EFI would cause the eventual "death" of carburetors. Carburetors were improving, and the future trajectory of EFI's progress was not at all clear (Norbye 1981, 7).

3.3 EFI and carburetor industry structure

The first firm to make and sell EFI systems was Bosch, a German automobile supplier. Because EFI was first marketed by Bosch, a third–party supplier, from very early on the technology was available to manufacturers to purchase the components and apply the technology to their vehicles. Interviews and an extensive search have failed to show any evidence that access to EFI components was restricted in any way based upon the identity of the customer. Bosch EFI systems were sold in automobiles produced by Swedish, German, Japanese, and American firms. A number of automobile manufacturers had divisions within the firm that produced EFI systems, including Ford, General Motors, and Toyota. Other parts suppliers also offered EFI as component systems. One significant fact about fuel delivery system production, which will be useful when examining the question of whether threatened firms try harder, is that some firms produced both EFI and carburetors, and some produced only carburetors or EFI. At least two significant American OEMs, Carter and Holley, built carburetors but did not produce EFI systems.

3.4 The carburetor's last gasp

Carburetor efficiency can be measured on several dimensions. Of these, the most important is fuel consumption, although carburetor design also affects emissions performance and drivability. Carburetor emissions performance is impossible to separate from the performance of other emissions control components, which are unobserved in the data. Furthermore, emissions performance is an all-or-nothing proposition—a car meets standards or it doesn't. During the period of observation, it was very difficult for a consumer to discover the emissions performance level of a given automobile, and the manufacturer was given no credit in the regulatory environment for overachieving. Drivability is difficult to operationalize, and it is not observed in these data. In the end, fuel efficiency is the metric that best measures a carburetor's performance in its intended role. It is rewarded by the market and by government regulators. So for the purposes of this paper, I define carburetor efficiency as the fuel consumption performance of a carburetor-equipped car.

A plot of fuel efficiency over time shows that, after the introduction of EFI, cars equipped with carburetors exhibited dramatically increased fuel efficiency (see Figure 2 on the next page). This is similar to observations others have made about sailing ships after the entry of steam power (Gilfillan 1935a), and ice harvesting after the appearance of mechanical refrigeration (Utterback 1994). In the following sections, I will analyze to what extent selection, spillovers, and trying harder were responsible for the last gasp in Figure 2.

4 Data

The data for the analysis in this paper come from two sources. The first is a dataset 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. Observations include variables measuring each car's physical characteristics—weight, car class, number of doors, type of engine, size of engine, type of transmission, type of fuel delivery system, and presence of engine management computer. The unit of observation is a car model, which is any available

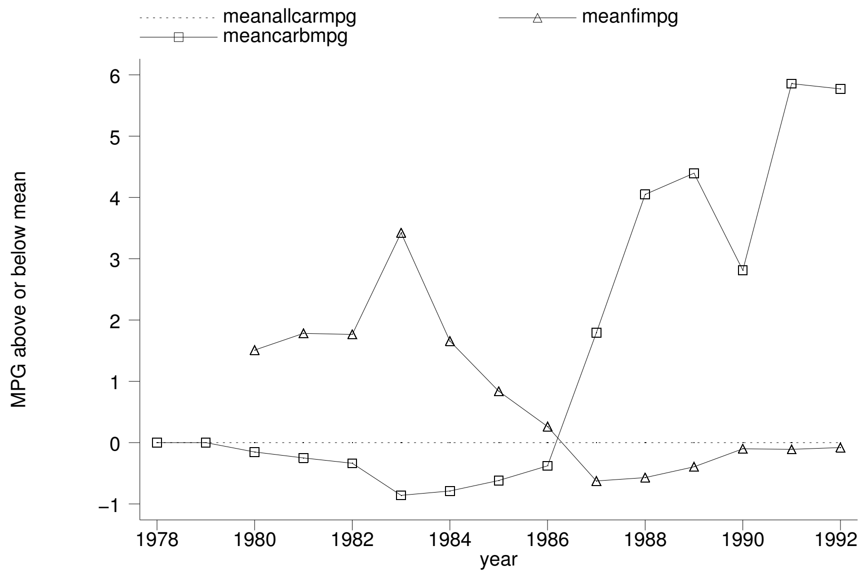

Figure 2: Mean Carburetor and EFI MPG versus Mean Car MPG for Models sold in US

combination of model name, body type, engine size, transmission type, power output, and carburetor or EFI. I have merged this dataset with a second dataset from the EPA containing test results for all cars that are eventually approved for sale in the United States. This dataset contains results from EPA tests of each car's horsepower, fuel economy performance (MPG) on city and highway cycles, and emissions performance. Finally, for a subset of the data, I use carburetor repair manuals to identify which firms manufactured an automobile's carburetor.

The final dataset contains 10,507 car models, an average of about 700 per year from 1978 through 1992. At the start of the sample, carburetors are found in 100 percent of the models. The first EFI systems appear in cars in 1980, and they take market share from carburetors until, by 1992, carburetors are almost completely displaced from the market. Cars become lighter during the early 1980s in response to the gas crisis and recession. After 1985, however, cars become steadily heavier. Descriptive statistics are reported in Table 1 on page 28.

For testing the trying harder explanation, I use carburetor repair manuals to identify a subset of carburetors built by two carburetor–only firms, Carter and Holley. These firms are likely to have been the ones most threatened by EFI's challenge. This subset contains 595 car models, distributed over eleven years. Table 2 on page 28 reports descriptive statistics for this group of automobiles.

5 Empirical Results

I begin with a simple specification in which the fuel efficiency (in *MPG*) of car model i is regressed on an interaction between the car's fuel system (*EFI* or *Carb*), the car's year of production *ModelYear* and for the carbureted cars, whether that production took place in the pre–EFI (*Pre1984*) or post-EFI (*Post1983*) period.

$$\begin{aligned} MPG_i &= \beta_1(ModelYear*Carb*Pre1984)_i \\ &\quad +\beta_2(ModelYear*Carb*Post1983)_i \\ &\quad +\beta_3(ModelYear*EFI)_i + \delta(X)_i + \epsilon_i \end{aligned} \tag{1}$$

The vector X contains carburetor fixed effects for the *Pre1984* and *Post1983* period, respectively. The coefficient β_1 measures year–to–year gains in fuel efficiency for carbureted cars in the pre–EFI period, while β_2 measures growth in the post–EFI period. The coefficient β_3 measures annual growth in EFI efficiency. This base specification does not account for the possibility that automobiles, the technology they contain, or the organizations that produce them, might have been changing during this time period. In the next section, I will allow for that possibility.

The results show that carburetors show a greater rate of efficiency improvement after the entrance of EFI (see regression 1 in Table 4 on page 29). The fuel efficiency of carbureted cars produced through 1983 grew by about .35 MPG (β_1) per year. The fuel efficiency of carbureted cars produced after 1983 grew by about .86 MPG (β_2) per year. The difference, ($\beta_2 - \beta_1 = .51$) is positive and statistically significant. To provide a comparison, average carbureted automobile MPG during this period was between 20 and 26 MPG. Thus, without controlling for selection, the data appear to show a last gasp. One indication that there may be a selection effect unaccounted for in this specification is that β_3 is negative, indicating negative efficiency growth in EFI.

The last gasp finding is not sensitive to moving the pre– and post–EFI–introduction date from 1982 through 1986. This is the range during which one might expect that carburetor manufacturers began to respond to the entry of EFI.

I conclude that there was a significant jump in annual fuel efficiency growth among car models equipped with carburetors. The remainder of this section tests whether I can find support for the selection, spillovers, and trying harder hypotheses to explain this finding. Because selection issues are of concern in all explanations, I analyze selection first.

5.1 Selection

The selection explanation hypothesizes that automakers systematically equipped certain types of cars with carburetors and other types of cars with EFI. If automakers tended to put EFI systems into cars that otherwise would have had low fuel efficiency, leaving carburetors in cars that were already fuel efficient, then changes in average fuel consumption in the population of carbureted cars will overstate the efficiency gains for the average carbureted car.

To determine whether selection explains the increases in carburetor efficiency I found in the base specification, I first test whether the types of cars which carried carburetors actually changed. I then control for the possibility that the choice of model in which to install EFI might have been endogenous to the car model's fuel efficiency.

There is evidence that the types of cars equipped with carburetors changed after the arrival of EFI. Figure 3 contains a plot of mean annual horsepower and weight for EFI– and carburetor–equipped automobiles over time. Horsepower and weight are the most important determinants of fuel efficiency, other than the fuel delivery system. The figure indicates that carburetors are being displaced from heavier, more powerful cars.

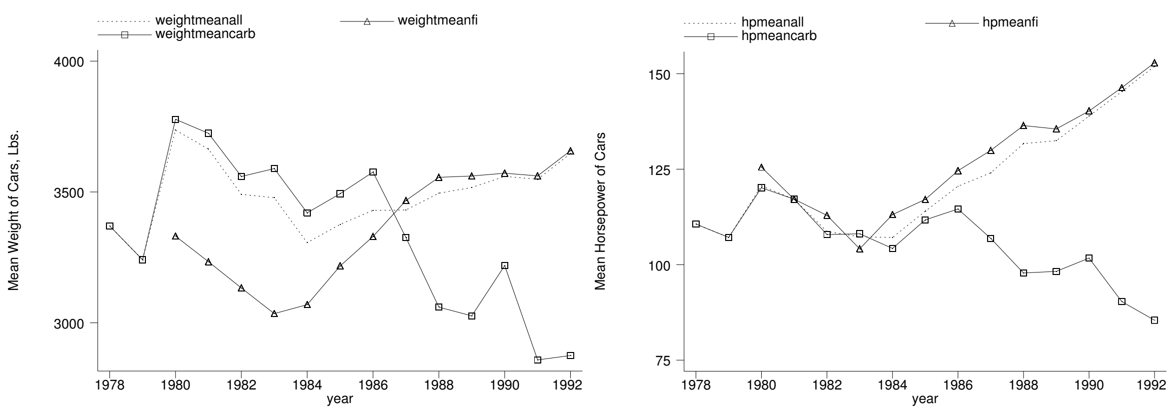

Figure 3: Mean Weight and Horsepower of EFI- and Carb-Equipped Cars

Table 3 on page 29 shows a regression of fuel economy on a car model's weight and horsepower for the whole sample. It shows that increased weight and increased power reduce fuel economy. The addition of 1000 pounds reduces MPG by 5.3 MPG. In fact, weight and horsepower, in combination with transmission type and engine displacement, explain much of the variance in *MPG* among car models —the regression in Table 3 on page 29 has an R-Squared of .74. If weight and power explain fuel efficiency this well, and they changed dramatically during the sample period, then this suggests that selection may drive the apparent increase in carburetor fuel efficiency.

To test this conjecture, I add controls for weight, horsepower, transmission type, and engine displacement to regression 1 to obtain regression 2:

$$\begin{aligned} MPG_i \quad = \quad & \beta_1(ModelYear^*Carb^*Pre1984)_i \\ & +\beta_2(ModelYear^*Carb^*Post1983)_i \\ & +\beta_3(ModelYear^*EFI)_i \\ & +\delta(X)_i + \gamma_1(Weight)_i + \gamma_2(Power)_i + \gamma \ldots + \epsilon_i \end{aligned} \tag{2}$$

The results differ dramatically from those obtained without controlling for weight, horsepower, transmission type, and engine displacement. Now, estimated annual carburetor efficiency growth *slows* after the entrance of EFI. The addition of weight and power turns the last gasp into a "last sigh." Annual carburetor efficiency growth, reported as regression 2 in Table 4 on page 29, goes from .80 MPG (β_1) per year before the entrance of EFI to .44 MPG (β_2) per year after. The difference in annual carburetor MPG growth per year between the two periods ($\beta_2 - \beta_1$) in the base specification was .51; in the new specification it is -.36 MPG. This is a negative and statistically significant change. Furthermore, the coefficient on EFI efficiency growth (β_3) is now positive, which is more plausible.

Controlling for car attributes would address selection concerns if auto manufacturers were choosing whether to equip cars with carburetors based solely on a car's weight and horsepower. However, if there are other, unobservable characteristics which jointly determine fuel efficiency and an automaker's decision of whether to use carburetors in a given car, then the coefficients and standard errors reported in regression 2 in Table 4 will be biased.

I control for selection using an instrumental variable (IV) in a two-stage least-squares (2SLS) regression. I construct an instrument for the presence of carburetors in a given car based on the notion that car engine attributes, regardless of manufacturer, determine whether a carburetor or EFI is a better fit for a given automobile. The instrument for the presence of a carburetor in a given car model is the carburetor penetration rate in car models built by different manufacturers, but that were built in the same year and have engines with the same number of cylinders and that are about the same size (less than 100 cubic centimeters of displacement different).

In notation, the instrument for an observation of car model i built by manufacturer j in model year k with engine type l is:

$$CarbInst_{ijkl} = \frac{\sum_{p \neq i} \sum_{q \neq j} CarModel_{pqkl,carburetor}}{\sum_{p \neq i} \sum_{q \neq j} CarModel_{pqkl,carburetor\underline{or}EFI}}$$

This measures the carburetor penetration rate for a given subset of cars. The numerator is the sum of all cars built in model year k with engine type l that are carbureted, but that are not model i and are not built by manufacturer j. The denominator is the sum of all cars built in model year k with engine type l that are carbureted or have EFI, but that are not model i and are not built by manufacturer j.

Regression 3 in Table 5 on page 30 reports the findings from the 2SLS specification. The results are different from those in regression 2, and provide evidence that selection does not explain the entirety of the last gasp. The new estimates of β_1 and β_2 are 1.22 and 1.48, respectively. Hence, the change in annual carburetor MPG growth per year $(\beta_2 - \beta_1)$ has gone from -.36 to +.26.

At this point, I conclude that carburetors' being shifted out of inefficient cars does not explain all the carburetor's last gasp. And now that I have controlled for selection, it becomes easier to examine whether the remaining last gasp efficiency improvements are attributable to mechanisms suggested by the other two explanations.

5.2 Spillovers

I now test another novel explanation for last gasps, namely that a technology introduced by an entrant technology may be adapted for use in the incumbent and therefore improve the incumbent's performance.

As discussed in section 3, one technology that moved from EFI to carburetors is electronic engine management systems. This technology allowed EFI to measure engine performance and to adjust operating parameters in real time. This technology was adapted to some carburetors. The EPA data contain a variable indicating the presence of a feedback fuel system (FFS), as they are called, in each car model observation.

To test whether the addition of feedback fuel system had an impact on carburetor efficiency growth, I add *FSS* to the 2SLS specification in regression 3. All EFI systems in the dataset have FFS, so FFS is only interacted with the *Year*Carb*Post1983* variable. This yields the following specification.

$$\begin{aligned} MPG_i \quad = \quad & \beta_1(ModelYear{*}Carb{*}Pre1984)_i \\ & +\beta_2(ModelYear{*}Carb{*}Post1983{*}FFS)_i \\ & +\beta_3(ModelYear{*}Carb{*}Post1983{*}NotFFS)_i \\ & +\beta_4(ModelYear{*}EFI)_i + \\ & +\delta(X)_i + \gamma_1(Weight)_i + \gamma_2(Power)_i + \gamma \ldots + \epsilon_i \end{aligned} \tag{4}$$

Supporting the spillover hypothesis, the addition of FFS increases carburetors' rate of improvement (see regression 4 on page 30). The average annual MPG growth rate for carbureted cars with FFS was higher than for carbureted cars without FSS, 1.90 (β_2) versus .73 (β_3). Among FFS–equipped cars, in fact, the pre–post change in annual carburetor MPG growth per year ($\beta_2 - \beta_1$) has increased from .26 in Regression 3, to .67 ($1.90 - 1.23$).

Whereas the improvements that resulted from selection didn't require any improvement in technology, the entrance of EFI seems to have improved carburetor efficiency through technological spillovers. One interpretation of the results in regression 4 is that selection explains away the carburetor's last gasp but that technology spillovers increased the magnitude of the original, apparent last gasp. These results seem to say that after the entrance of EFI, improvements to carburetors fell dramatically, but to the extent that carburetors did see efficiency growth, that improvement resulted from spillovers from EFI.

5.3 Trying Harder

Having shown that selection and technology spillovers help explaining the increase in the rate of efficiency improvement in carburetors, we come to the existing explanation, "trying harder." In this section, I continue to rely on the observation of MPG improvement to gauge whether there was a last gasp in carburetors. By focusing on outcomes (MPG), I will not observe efforts that did not result in actual efficiency growth. Thus, this section does not examine whether parties with vested interests in carburetors tried harder. Rather, it measures whether there is evidence of efficiency improvements that may have resulted from trying harder. This definition may cause me to overlook "unfruitful" trying harder.

To test the trying harder hypothesis, I identify a subset of cars in the dataset that were equipped with carburetors built by two carburetor manufacturers, Carter and Holley. Both of these firms produced only carburetors. They are identified in the data with an indicator variable *Pure*, while carbureters from all other firms, most of which produced both carburetors and EFI, are identified with an indicator variable *Mixed*. Neither Carter nor Holley offered EFI, and both subsequently were forced out of the OEM fuel delivery system industry.[3] This sample does not identify every firm that was threatened by the entrance of EFI. However, these two parts suppliers are the ones that that *should* have felt most threatened by the entrance and subsequent success of EFI.

Notice, however, that it is ultimately difficult to identify which firms are likely to have perceived EFI to be a threat and then to have tried harder (successfully) to increase carburetor

[3] Carter was purchased by an airplane parts manufacturer, and Holley became a niche player in the automotive performance parts industry.

performance. For example, we might expect suppliers that were fully devoted to carburetors to be the most threatened firms by the entrance of EFI. But carburetor–only firms probably chose their product portfolios based on their expectations about the relative potential growth of EFI and carburetor technology. Hence, firms that were fully dependent upon carburetors may not have felt threatened. If, however, carburetor–only firms realized they were "stuck" with carburetors after it was too late, they might have had reason to try harder because switching was no longer an option. This suggests the possibility of a "loser's curse"—those who perceive the risk from a substitute's entry to be lowest will also be those who are least prepared to respond to it.[4]

With this caveat about whether Carter and Holley are good examples of firms whose performance may have reflected trying harder, I proceed to test whether carburetors from those firms performed differntly from those of other firms.

To do this, I interact *Pure* and *Mixed* with groups used in prior specifications:

$$\begin{aligned} MPG_i \quad = \quad & \beta_1(\mathit{ModelYear*Carb*Pre1984*Pure})_i \\ & +\beta_2(\mathit{ModelYear*Carb*Pre1984*Mixed})_i \\ & +\beta_3(\mathit{ModelYear*Carb*Post1983*FFS*Pure})_i \\ & +\beta_4(\mathit{ModelYear*Carb*Post1983*FFS*Mixed})_i \\ & +\beta_5(\mathit{ModelYear*Carb*Post1983*NotFFS*Pure})_i \\ & +\beta_6(\mathit{ModelYear*Carb*Post1983*NotFFS*Mixed})_i \\ & +\beta_7(\mathit{ModelYear*EFI})_i \\ & +\delta(X)_i + \gamma_1(\mathit{Weight})_i + \gamma_2(\mathit{Power})_i + \gamma \ldots + \epsilon_i \end{aligned} \quad (5)$$

This specification generates evidence that pure–player carburetor manufacturers tried harder, and additional evidence of spillovers (see regression 5, Table 5 on page 30). The arrows in Table 5 illustrate how the addition of *Pure* bifurcates carburetor categories. Notice that carburetors from firms that eventually developed a mixed product portfolio (β_2) had faster rates of improvement in the pre–EFI period than did their pure–play carburetor counterparts (β_1). This can be interpreted in two different ways. It could mean that that firms working to develop EFI were capturing spillovers of some type in the performance of their then–current products. Reversing the causality, we might imagine that the fittest firms were the ones that had the resources to expand their product portfolios eventually.

Regression 5 also shows that the pure–player carburetor firms received no benefit from

[4]This term was first suggested by Meghan Busse.

spillovers of FFS technology ($\beta_3 - \beta_5 = .55 - 1.48 = -.93$). In fact, annual carburetor MPG growth within Carter and Holley was actually higher for non-FFS equipped carburetors than it was for FFS–equipped carburetors. One interpretation of this result is that firms involved in the next generation of technology are better equipped to apply that technology to the current generation.

This interpretation is reinforced by looking at where mixed–portfolio carburetor manufacturers obtained improvements. FFS–equipped carburetors from these firms had dramatically better rates of improvement than did non–FFS–equipped carburetors from mixed–portfolio firms ($\beta_4 - \beta_6 = 1.95 - .69 = 1.26$). Again, this points to the possibility that firms involved in EFI were better equipped to adapt FFS technology to carburetors.

Finally, regression 5 provides ambiguous results for the explanation that threatened firms improved their carburetors' rate of performance performance in a way that cannot be explained by selection or spillovers. Non–FFS–equipped carburetors from pure–player carburetor manufacturers had a higher rate of efficiency growth than did non–FFS–equipped carburetors from mixed–portfolio carburetor manufacturers ($\beta_5 - \beta_6 = 1.48 - .69 = .79$). However, it is not clear whether this is an artifact of mixed–player manufacturers abandoning non–FFS carburetor development or whether it reflects a real performance difference that resulted from trying harder.

These empirical results show that the last gasp of carburetors can be explained by a change in carburetor application and technology spillovers from an entrant technology, EFI. Furthermore, they seem to show that firms that were involved in the development of the new technology had an advantage in capturing the spillover benefits from the entrant technology. Finally, in the case of the carburetor's last gasp, there is ambiguous support for the hypothesis that threatened firms improve their performance in the face of a challenge from an entrant technology.

6 Patent Data Analysis

Up to this point in this paper, I have used automobile fuel efficiency data to measure carburetor efficiency. Although automobile MPG is a good measure of individual carburetor efficiency, there are two important limitations to its usefulness in the context of this paper. First, it does not describe the technological content of individual carburetors. I am left to make inferences about the sources of firms' carburetor technology based upon observations of their products. Second, MPG is a measure of performance outcomes, so I am left to make inferences about each firm's effort and input based on observed performance of its products. To understand whether how last gasps mechanisms work inside firms, then I need to measure and describe the inputs to the EFI and carburetor innovation.

In this section, I use patent data (Hall et al. 2001) to address some of the limitations of the EPA automobile performance data. This section is structured as follows. First, I describe the patent data. Second, I address the spillovers explanation, focusing on the sources of intellectual property in the automobile fuel delivery industry. Finally, I address the trying harder explanation, focusing on the innovative behavior of threatened carburetor firms.

6.1 The Patent Data

This study is particularly well-suited to the use of patent data for two reasons. First, the World Intellectual Property Organization's (WIPO's) International Patent Classifications (IPC) system contains distinct classifications for carburetors and for EFI, which allows me to examine innovative activity within these two technology spaces. And second, there are many fuel delivery patents during the period with which we are concerned.

From 1970 through 1999, the USPTO issued 9506 patents in 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 patenters are Bosch (125 patents), Honda (69), Toyota (58), Nippondenso (46), and Hitachi (45).

6.2 Examining Spillovers using Patent Data

The empirical evidence presented in this paper shows that the addition of Feedback Fuel System (FFS) electronics to carburetors caused a significant increase in carburetor performance growth. Additionally, I have shown that carburetors built by dual-product carburetor/EFI firms benefited more from the addition of Feedback Fuel System (FFS) electronics developed for use in EFI systems than did carburetors built by carburetor–only firms. I have interpreted this result as evidence that spillovers from entrant technologies to incumbent technologies are more efficiently captured within firms. This interpretation is consistent with Cohen and Levinthal's "Absorptive Capacity" theory, which says that "the ability to evaluate and utilize outside knowledge is largely a function of the level of prior related knowledge" (1990). In the context of these spillovers, the Absorptive Capacity theory says that the firms which developed their own EFI systems were best able to adapt that new technology to carburetors. If this is a correct interpretation of the data, then the presence of these spillovers is an as–yet unexplored factor for firms to consider when deciding whether to source next–generation technology from within or from outside the firm.

An alternative to the Absorptive Capacity explanation is that an unobserved variable, something I'll call firm "innovativeness," causes firms' product mix as well as firms' level of success in adapting FFS electronics to carburetors. This explanation says that although many firms in the fuel delivery industry may have developed EFI systems, only the most innovative firms succeeded at bringing EFI to market. Not surprisingly, the innovative firms were also the firms that were most successful at improving their carburetors by adding FFS electronics.

This potentially unobserved variable is problematic because I may have identified Carter and Holley as carburetor–only firms when in fact they might have been merely "non–innovative" firms. And if that "non–innovativeness" caused Carter and Holley to be unsuccessful in their ostensible attempts to market EFI systems, then I have incorrectly identified them as "carburetor–only" firms. In other words, if Carter and Holley were innovating in the EFI technology space, then Absorptive Capacity is not a good explanation for the observation that Carter and Holley were worse at applying FFS electronics to carburetors. So, in sum, my inability to observe Carter's and Holley's level of "innovativeness" independent of their product portfolio composition, means that I can't reject "innovativeness" as an alternative explanation to Absorptive Capacity.

To address this potential unobserved variable problem, I examine the patenting activity of automobile fuel–delivery system producer firms. I use a direct measure of "innovativeness"—whether a firm owns patents both in carburetor and in EFI categories—in concert with the repair manual data to determine whether the threatened carburetor firms were involved in EFI innovation but did not successfully market EFI systems. If Absorptive Capacity is responsible for the integrated product firms' success in adapting FFS to carburetors, then one refutable prediction is that Carter and Holley were not involved in EFI technology development in any significant way.[5]

Figure 4 on the next page shows assignee carburetor and EFI patent counts. This plot shows that many assignees were involved in innovative activity in both technology spaces. Carter held 43 carburetor patents and no EFI patents. Holley held 28 carburetor patents and 4 EFI patents. The average assignee with both types of patents in its portfolio held 21.2 carburetor patents and 14.1 EFI patents. These counts show that we have accurately identified Carter as being a "carburetor-only" firm. Holley, while not being "carburetor-only," was "carburetor-heavy."[6] In Carter's, and to a lesser extent, Holley's case, this patenting activity is consistent with

[5]Another test of these two explanations for why spillovers were more effective within firms would exploit variation in patenting behavior of firms in the industry as an instrument for firm quality in the MPG regressions. A future step in my research is to match the EPA dataset to the patent dataset, which will make it possible to include firm innovative activity as an instrument in my existing analysis.

[6]In future research, I will examine Carter and Holley individually, potentially making use of variation in the level to which each was threatened by EFI.

Absorptive Capacity's prediction, so we can't reject it as an explanation for mixed–product firms' success at adapting FFS to carburetors.

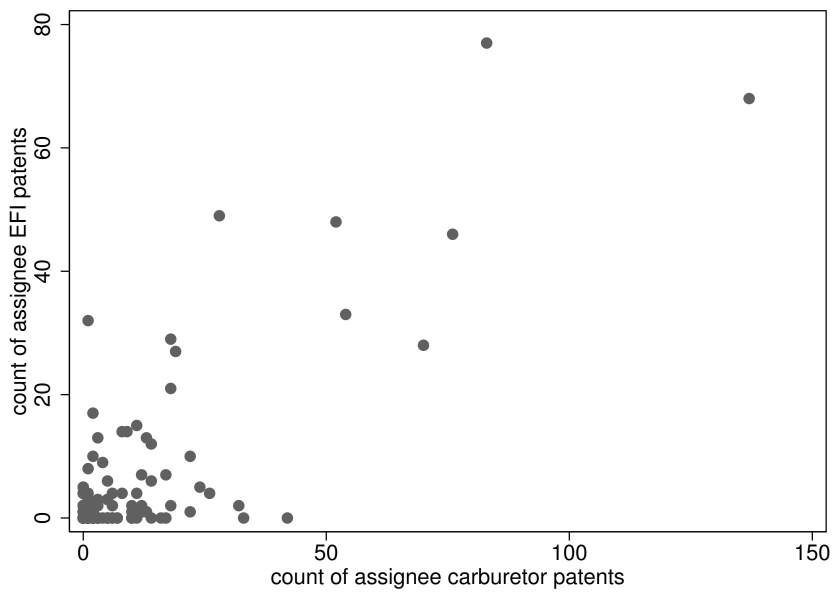

Figure 4: Carburetor and EFI Patents Counts by Assignee

The patent data provide another opportunity to check whether I have accurately described the spillover story. Implicit in the Absorptive Capacity story in this paper is the notion that EFI innovation is the price of admission to the efficient use of FFS in carburetor applications. If this notion is correct, then I expect to find that EFI innovators are more likely than are carburetor innovators to be FFS innovators. In the context of the patent data, I expect to find that EFI patent assignees are more likely than are carburetor patent assignees to hold FFS patents. To test this, I collapse the patent data into a dataset of firms that have patented in the FFS, EFI, or carburetor categories. In the following regression,

$$\begin{aligned} FFSpatenter_i \quad = \quad & \beta_1(EFIpatenter)_i \\ & +\beta_2(Carbpatenter)_i \\ & +\beta_3((Bothpatenter))_i + \epsilon_i \end{aligned} \tag{6}$$

a dummy variable *FFSpatenter*, indicating whether firm i holds FFS patents, is regressed on dummy variables *EFIpatenter*, *Carbpatenter*, and an interaction term *Bothpatenter*. These dummies indicate whether firm i holds EFI patents, carburetor patents, or both. The results, reported in regression 6 in Table 6 on page 31, show that being a carburetor innovator (β_1) does not have a significant independent effect on the likelihood of an assignee becoming an FFS innovator. But the estimated value of coefficient β_2, is .129 and significant, meaning that an EFI innovator is about 13 percent more likely to be an FFS innovator than is a non-EFI innovator. The estimated value of β_3 is .433, which means that holding carburetor patents makes an EFI innovator 30 percent ($\beta_3 - \beta_2$) more likely to be an FFS innovator. Again, these findings are consistent with the story of FFS innovation in this paper.

6.3 Examining Trying Harder using Patent Data

The empirical evidence presented in this paper indicates that a small portion of the carburetor's last gasp can be explained by extraordinary improvements in carburetors built by firms that were threatened by the entrance of EFI. I have interpreted these carburetor performance improvements as evidence that threatened firms tried harder. But it is not clear whether threatened firms increased their effort to achieve these product improvements or whether some other, unobserved factor was responsible for these improvements.

I would have more confidence that I am observing "trying harder" behavior among the threatened firms if I were to observe changes in a more proximate measure of effort than is product performance. The efficiency measure, MPG, that I have used in this paper can be thought of as a measure of firm output. But it is probably not a good measure of inputs or effort, which is what the trying harder story is concerned with. So I need to find a measure of firm inputs and check whether the pattern of inputs is consistent with the trying harder story. With perfect data, I might observe some firms becoming more innovative, inspiring their employees, and streamlining their organizations, while at the same time observe those firms obtaining poor results in the realm of product efficiency. But if trying harder explains the improvements in Carter's and Holley's carburetors, then we should expect to find that their efforts, independent of their product improvements, increased after the threat from EFI appeared.

I use patent data to examine whether threatened firms' innovative activity changed after the appearance of EFI.[7] Although innovative activity is not the only indicator of firm effort, it is an important one. Advances in product efficiency require innovative activity within the firm, so I expect to observe innovative activity preceding product improvements. In other words, for organizational efforts such as streamlining or increased workforce utilization to impact product efficiency, they are likely to "pass through" innovative activity on their way to becoming product

[7] A well-developed literature has exploited patent data to measure innovative activity in firms. See Griliches (1990, 1995); Pavitt and Patel (1995).

efficiency improvements.

During the 1970 to 1999 period, Carter was granted 43 carburetor patents and Holley was granted 28 carburetor patents. Annual carburetor patent counts for Carter and Holley are plotted together with total carburetor category patent counts in figure 5.

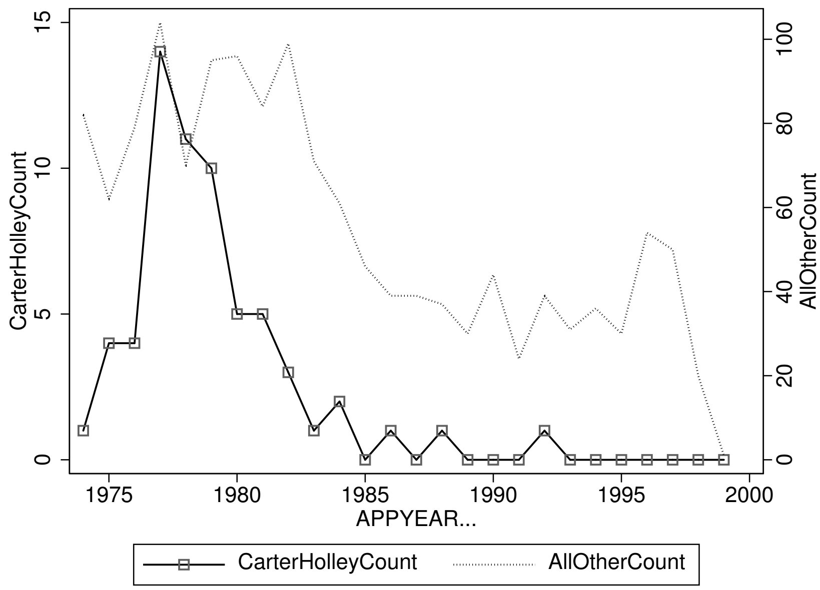

Figure 5: Annual Carburetor Patent Counts: Carter and Holley vs. All Others

To test for whether the Carter and Holley observed product efficiency improvement was a result of increased effort, I examine their patenting behavior for two specific patterns in the data. The first test is whether the Carter and Holley rate of carburetor patent generation increased after the introduction of EFI. Second, I ask whether the Carter and Holley patent generation behavior looks different from that of other carburetor patent assignees. These two tests look for extraordinary patenting behavior using two different counterfactuals against which to compare Carter's and Holley's activities. The first counterfactual is the Carter and Holley rate of patent production before the arrival of EFI. The second counterfactual is the "all-other-assignees" rate of carburetor patent production. The second counterfactual allows for the possibility that the "natural" rate of innovation production might have been falling at an increasing rate in the carburetor category, but that the trajectory of threatened firms did not accelerate downward as quickly as did that of other firms—a sign that threatened firms had increased effort. The patent generation trajectories in Figure 5 don't provide obvious evidence one way or the other—any change in threatened firm behavior is too subtle to see without a regression.

To test whether Carter and Holley carburetor patenting behavior changed after the introduction of EFI, the carburetor patents in the dataset are divided among four mutually exclusive bins—whether they came from a threatened assignee (Carter and Holley) or from another assignee, and whether they were applied for before or after the EFI's entry. The following regression

$$\begin{aligned} Yearcount_i \quad = \quad & \beta_1(Appyear{*}CarterHolley{*}Before)_i \\ & +\beta_2(Appyear{*}CarterHolley{*}After)_i \\ & +\beta_3(Appyear{*}NotCarterHolley{*}Before)_i \\ & +\beta_4(Appyear{*}NotCarterHolley{*}After)_i + \epsilon_i \qquad (7) \end{aligned}$$

estimates the rate of annual patenting growth in these four bins, with controls for assignee fixed effects. These annual rates are estimated for the period before 1984 and for the period after 1984, consistent with the pre– and post–EFI time periods used previously in the paper.[8] The estimates are reported in regression 7 in Table 7 on page 31). They show that carburetor patenting generally falls during the period of the sample—the estimated signs on β_1, β_2, β_3, and β_4 are negative, although the estimates of β_3 and β_4, the annual rates of patenting change among all non–Carter/Holley assignees, are not statistically significant.

Comparing the Carter and Holley patenting rate after EFI with the before–EFI rate, I find that it grew slightly ($\beta_2 - \beta_1 = (-0.0009) - (-0.0019) = .001$). This is evidence, albeit weak, in support of "trying harder" as an explanation for the observed improvement in Carter's and Holley's carburetors. To test the Carter and Holley post–EFI rate change against the rate change of all other assignees, we would need to have significant estimates for all of the categories. But because the estimates of β_3 and β_4 are not significant, we cannot test whether Carter and Holley's carburetor patenting rate growth is different from that of the industry as a whole. In the context of the real-world carburetor efficiency improvements, these results are quite small. While they do not allow me to reject the trying harder explanation, they do not provide significant evidence in support of it.

In sum, the patent database is a useful complement to product–level data in helping to explain the carburetor's last gasp. The patent data show patterns consistent with an Absorptive Capacity explanation for the apparent spillover of FFS electronics from EFI to carburetors. However, they do not provide evidence that Carter and Holley redoubled their efforts in response

[8]The results reported below do not change substantially if this cutoff is changed by up to two years.

to EFI's success in the market.

7 Conclusion

This paper examines the extent to which spillovers, selection, and trying harder contributed to a last gasp in automobile carburetor efficiency during the period in which Electronic Fuel Injection (EFI) entered and displaced carburetors from the market. Using detailed data on automobile characteristics and fuel efficiency, I find evidence that all three phenomena played a role. In particular, I find that as EFI was adopted, the subset of cars in which carburetors remained were lighter and less powerful than average, leading to observed fuel efficiency gains in carbureted cars that had nothing to do with technological change in carburetors themselves. This selection effect explains most of the last gasp that is observed when not controlling for car characteristics. However, this does not mean that there is no evidence for spillovers or trying harder in explaining changes in fuel efficiency in different vehicles. Indeed, the greater rate of fuel efficiency improvement in carbureted cars equipped with FFS suggests that spillovers from EFI technology were responsible for a substantial portion of the fuel efficiency increases carbureted cars experienced. Finally, there is ambiguous evidence that firms that were most committed to carburetor evidence of tried harder to generate efficiency improvements in the old technology.

This paper makes three contributions to the literature. The first is to bring to light automobile carburetors as a yet-unrecognized example of last gasps. The second is to introduce spillovers from entrant technologies to incumbent technologies as an explanation for last gasps. The third is to assess the relative importance of different explanations for last gasps, an endeavor that has not been possible previously because of a lack of sufficiently detailed data.

On a more general level, this paper provides insights on innovation, especially about innovation in competitive and transitional environments. The example of carburetors and EFI suggests, for example, that a substitute technological innovation may have a larger effect on the applications of an existing technology than on the technology itself. The results also suggest that substitute technologies can generate important spillovers via components. While in the case of carburetors, the more efficient components were not enough to preserve it as a viable technology, mutual spillovers may explain why some substitute technologies coexist. In this sense, the lessons to be learned from last gasps may be valuable in understanding innovation throughout a technology's life.

Table 1: Summary Statistics

	Obs	Carbs	MPG	Weight (lbs)	Horsepower
	N	N	mean	mean	mean
1978	420	420	21.98	3370	110.6
1979	438	438	22.17	3241	107.1
1980	621	564	20.24	3737	120.6
1981	618	542	21.98	3664	117.1
1982	754	633	23.86	3491	108.7
1983	797	637	24.68	3478	107.3
1984	560	378	25.72	3306	107.1
1985	778	448	25.66	3376	114.0
1986	794	322	25.49	3430	120.5
1987	816	208	25.65	3431	124.0
1988	783	96	25.47	3495	131.7
1989	741	59	25.37	3518	132.5
1990	802	24	25.36	3561	139.0
1991	817	15	25.42	3549	145.3
1992	799	11	25.04	3647	151.9

Table 2: Summary Statistics for Subset of Models from Carb–Only Firms

	Obs	MPG	Weight (lbs)	Horsepower
1978	27	24.93	2991	80.9
1979	38	22.45	3316	103.2
1980	79	18.61	3921	116.2
1981	79	21.48	3643	109.6
1982	80	22.48	3645	109.1
1983	103	22.25	3653	114.8
1984	69	25.01	3348	104.8
1985	52	25.39	3409	117.1
1986	37	22.18	3851	123.5
1987	29	22.58	3853	119.9
1988	2	22.30	3938	138.0
1989-1992	–	–	–	–

Table 3: Regression Showing Determinants of MPG

	combmpg
weight1000	-5.130
	(0.100)**
power	-0.011
	(0.001)**
displtrs	-1.050
	(0.047)**
auto	-1.100
	(0.064)**
Constant	47.693
	(0.280)**
Observations	10505
R-squared	0.74

Table 4: Tests of Explanations for Last Gasps†

	(1)	(2)
yearxcarbxpre	0.346	0.801
	(0.093)**	(0.045)**
yearxcarbxpost	0.858	0.442
	(0.090)**	(0.043)**
yearxfi	-0.093	0.382
	(0.028)**	(0.015)**
carbxpre	-664.082	-1,538.486
	(183.870)**	(89.347)**
carbxpost	-1,678.162	-826.419
	(178.155)**	(85.464)**
fi	210.245	-707.710
	(54.682)**	(28.786)**
weight		-0.006
		(0.000)**
power		-0.037
		(0.001)**
auto		-1.254
		(0.057)**
dispcc		0.000
		(0.000)**
Observations	10507	10505
R-squared	0.93	0.99

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

† Coefficient estimates for interacted variables are interpretable without being added to other coefficients. The interacted variables create mutually exclusive and exhaustive categories for the observations in the data.

Table 5: Second Stages of 2SLS Regressions for Last Gasps[†]

	(3)	(4)	(5)
yearsmxcarbxpre	1.217 (0.071)**	1.231 (0.072)**	
yearsmxcarbxprexpure			1.023 (0.168)**
yearsmxcarbxprexmixed			1.233 (0.074)**
yearsmxcarbxpost	1.483 (0.125)**		
yearsmxcarbxpostxffs		1.903 (0.187)**	
yearsmxcarbxpostxnotffs		0.729 (0.144)**	
yearsmxcarbxpostxffsxpure			0.550 (0.197)**
yearsmxcarbxpostxffsxmixed			1.951 (0.198)**
yearsmxcarbxpostxnotffsxpure			1.479 (0.251)**
yearsmxcarbxpostxnotffsxmixed			0.688 (0.147)**
yearsmxfi	0.530 (0.023)**	0.539 (0.024)**	0.536 (0.024)**
weight	-0.011 (0.000)**	-0.011 (0.000)**	-0.011 (0.000)**
power	-0.047 (0.002)**	-0.048 (0.003)**	-0.048 (0.003)**
auto	-1.401 (0.079)**	-1.400 (0.081)**	-1.385 (0.081)**
dispcc	0.002 (0.000)**	0.002 (0.000)**	0.002 (0.000)**
carbxpre	54.336 (0.871)**	54.729 (0.934)**	
carbxprexpure			53.782 (1.069)**
carbxprexmixed			54.660 (0.940)**
carbxpost	50.911 (0.739)**		
carbxpostxffs		47.875 (0.991)**	
carbxpostxnotffs		56.854 (1.322)**	
carbxpostxffsxpure			56.709 (1.648)**
carbxpostxffsxmixed			47.419 (1.076)**
carbxpostxnotffsxpure			50.500 (1.753)**
carbxpostxnotffsxmixed			57.057 (1.360)**
fi	57.649 (0.923)**	58.096 (0.993)**	57.963 (0.993)**
Observations	8955	8955	8955

Robust standard errors in parentheses; * significant at 5%; ** significant at 1%.
[†] Coefficient estimates for interacted variables are interpretable without being added to other coefficients. The interacted variables create mutually exclusive and exhaustive categories for the observations in the data.

Table 6: Who Holds FFS Patents Linear Probability Model

	(6) FFSpatenter
Carbpatenter	-0.003
	(0.018)
EFIpatenter	0.129
	(0.031)**
Bothpatenter	0.433
	(0.044)**
Constant	0.032
	(0.009)**
Observations	1017
R-squared	0.28

Standard errors in parentheses; * significant at 5%; ** significant at 1%.

Table 7: Annual Patent Rate Change Fixed Effects Regression

	(7) yearcount
appyearxcarterholleyxbefore	-0.0019
	(0.0004)**
appyearxcarterholleyxafter	-0.0009
	(0.0004)*
appyearxnoncarterholleyxbefore	-0.0000
	(0.0000)
appyearxnoncarterholleyxafter	-0.0000
	(0.0000)
Constant	0.3119
	(0.0148)**
Observations	7020
R-squared	0.06

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

† Coefficient estimates for interacted variables are interpretable without being added to other coefficients. The interacted variables create mutually exclusive and exhaustive categories for the observations in the data.

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