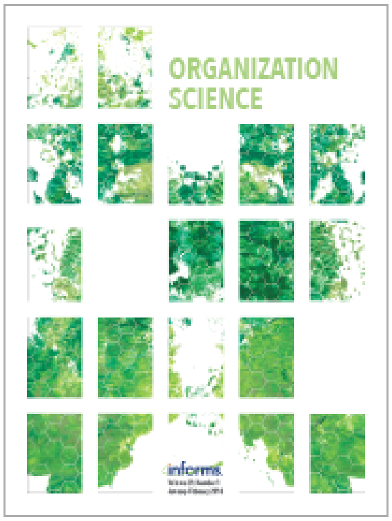

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Intergenerational Hybrids: Spillbacks, Spillforwards, and Adapting to Technology Discontinuities

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During technological discontinuities, incumbents frequently develop hybrids of competing technical generations. Although some prior work implies that such intergenerational hybrids may be the result of organizational dysfunction, we propose that in some cases hybrids may be sophisticated learning tools that shape organizational adaptation to a technological discontinuity. In this paper, we suggest two mechanisms through which intergenerational hybrids may affect organizational adaptation: spillbacks and spillforwards. In an empirical test among the population of automobile carburetor manufacturers during a technological discontinuity, we observe that organizations developing intergenerational hybrids capture spillback benefits—knowledge spillovers from an emerging technology generation to the current generation. Furthermore, we find that these same organizations also capture spillforwards—spillover benefits from developing higher-performing intergenerational hybrids that improve their product performance in the future technology generation. These results suggest that intergenerational hybrids may be stepping-stones for organizations to learn about and adapt to technology discontinuities.

Keywords: uncertainty; technology discontinuities; organizational adaptation; knowledge recombination; innovation
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Introduction

Technology discontinuities frequently destroy the advantages of incumbent organizations as new technologies replace older technologies (Tushman and Anderson 1986). Prior research highlights that incumbents struggle to respond for many reasons, including organizational inertia and reluctance to abandon their existing resources (Agarwal and Bayus 2002, Agarwal and Tripsas 2011, Benner 2009, Gilbert 2005, Henderson 1993, Tripsas 2009). As incumbents attempt to respond to the potential undermining of their existing technologies and resources, qualitative observation suggests that such organizations often recombine old and new technologies to create intergenerational hybrids. For example, when steam power threatened sailing ships, manufacturers of sailing ships integrated steam engines into sailing vessels to improve in-harbor navigation performance. Similarly, when personal computers threatened typewriters, typewriter makers integrated CRT displays, disk drives, and integrated memory circuits to create a hybrid dedicated “word processor.” Although intergenerational hybrids appear with surprising frequency during the interval between technology generations, in contrast to the more common intragenerational forms of technology recombination (Fleming 2001, Katila and Ahuja 2002, Kogut and Zander 1992, Levinthal 1998), intergenerational hybrids have received limited study. As a result, we know little about the development of intergenerational hybrids and the role these hybrids play in incumbents’ efforts to adapt to technology discontinuities.

The predominant view of intergenerational hybrids in existing qualitative accounts suggests that such hybrids may be the physical instantiation of organizational inertia. Understandably, after a technology discontinuity, intergenerational hybrids (such as the hybrid sailing ship or word processor) may appear as inadequate “half steps” between generations. For example, when photo typesetting displaced the old hot metal architecture, the Mergenthaler Linotype Company developed a hybrid between the two generations that, in retrospect, was clumsily anchored in the old technology (Tripsas 1997b). Hence, existing accounts have associated hybrids with an incumbent’s inability to abandon its existing knowledge and resources, impeding the organization’s efforts to adapt to a technology discontinuity (Henderson and Clark 1990, Rosenbloom 2000, Sull et al. 1997).

However, although there are clearly cases in which intergenerational hybrids are associated with organizational inertia, we suggest that there may be circumstances under which an intergenerational hybrid allows an organization to learn about an uncertain technological future. Although technology discontinuities appear certain ex post, when viewed ex ante, threatening technology discontinuities are highly uncertain. For example, threatening technologies may fail to displace old technologies (Adner and Kapoor 2010, 2012), incumbents may leap too early into the new technology before market takeoff (Gilbert 2005, Utterback 1996), institutional forces may delay a discontinuity (Ansari and Garud 2009), customer preferences may shift if and when a technology wins (Adner and Snow 2010b, Eggers 2012), or bottlenecks in the ecosystem may limit the scope of the technology threat

(Adner 2012, Tripsas 1997b). Under these conditions of uncertainty, developing an intergenerational hybrid may provide incumbents with a mechanism to span the uncertainty and learn about the as yet undetermined technology future (Furr and Snow 2014, Wu et al. 2014). Specifically, developing an intergenerational hybrid could allow a firm to develop supply-side knowledge (e.g., knowledge of technology characteristics, production), demand-side knowledge (e.g., knowledge of heterogeneous customer preferences, marketing messages), or timing knowledge (e.g., knowledge of when technology substitution might occur) that could help an organization adapt to the technology discontinuity. For example, hybrid 2.5G mobile networks allowed mobile operators to bridge technical and market uncertainty during the long transition between voice-centric 2G networks and data-centric 3G networks (Ansari and Garud 2009). Even if the threatening discontinuity fails to take hold, by investing in an intergenerational hybrid, an organization may avoid wasting the resources involved in taking a full step into the new technology, while potentially borrowing knowledge from the threatening technology that could improve the organization's existing offerings.

Naturally, the probability and impact of intergenerational hybrids are bounded by certain conditions. The probability of intergenerational hybrids appearing during a technology discontinuity depends on several factors, most importantly the existence of modular components in the different generations that can be recombined or architectures that can be substituted or modified between generations. The impact of intergenerational hybrids on organizational learning about a threatening technology may be limited by several factors, especially if the firms producing hybrids incorporate less relevant technologies (e.g., develop hybrids with the "losing" technology among competing variants in the new technology generation), underinvest in the new technology (e.g., develop hybrids that function to preserve the old technology rather than integrate the new technology), or invest at a less appropriate time (e.g., produce hybrids after a discontinuity has already occurred). For example, Kodak's APS photo system (which embedded magnetic data strips in film) likely served to extend the old film technology more than it helped the company learn about digital photography (Cohen and Tripsas 2014). By contrast, when Nikon developed a hybrid digital SLR camera, the process helped the organization learn about the future technology and eventually develop digital cameras. Therefore, a hybrid that integrates components from the new technology generation may allow a firm to learn about the technology as well as the nontechnical complementarities (customer preferences, institutional constraints, etc.) that affect the transition (Teece 1986, 2006).

Given our limited, even conflicting, understanding of how intergenerational hybrids impact organizational learning about an adaptation to technological discontinuities, in this paper we ask two questions: (1) How do different types of knowledge possessed by organizations impact the development of intergenerational hybrids? And (2) how does the performance of hybrids of the old and new technologies affect performance after a technology discontinuity? To answer these questions, we propose two previously unexplored learning mechanisms that affect the role of intergenerational hybrids in technology competitions: spillbacks and spillforwards. Spillbacks are knowledge spillovers from a threatening technology regime to an incumbent technology regime through an intergenerational hybrid. Spillforwards are knowledge spillovers, accrued while creating an intergenerational hybrid, that spill forward into a future technological regime, potentially aiding organizations in their efforts to adapt to a technology discontinuity.

We explore these questions in the context of the automobile industry, when carburetors were replaced by electronic fuel injection (EFI) systems. We use a data set composed of the full population of manufacturers and every carburetor produced for the U.S. automobile market from 1978 to 1992. We argue that greater investments in inventive knowledge in the extant carburetor regime and the threatening EFI regime, as well as more generalized inventive knowledge, could contribute to spillbacks, measured as the performance of intergenerational hybrid carburetors. We then explore how the performance of hybrids contributes to spillforward benefits—namely, greater-than-expected performance of an organization's products in the new generation after the technological discontinuity.

We find significant evidence that the greater an organization's investment in the new technology, the greater the performance spillbacks it captures as it borrows from the future technology to improve its current technology. More surprisingly, we find that, despite some interpretations of intergenerational hybrids as manifestations of organizational dysfunction, high-performing intergenerational hybrids appear to help organizations adapt to technological discontinuities, increasing their performance in the new technology relative to competitors in the postdiscontinuity environment. In other words, our results suggest that hybrids, within certain boundary conditions, can help organizations span and adapt to technology discontinuities, increasing their ability to compete in the next technology generation.

Theory

Among the events to which organizations must adapt, the punctuated equilibrium nature of technology discontinuities makes them extremely challenging (Gersick 1991, Rosenkopf and Tushman 1994, Tripsas 1997a, Tushman and Anderson 1986). A growing body of literature has examined the factors that influence the ability of incumbents to adapt to such discontinuities.

Research suggests that organizational processes (Benner and Tushman 2002, Henderson and Clark 1990), cognition (Eggers and Kaplan 2009, Furr et al. 2012, Tripsas 2009), resources and capabilities (Gilbert 2005, Rosenbloom 2000), complementary assets (Adner and Kapoor 2012, Tripsas 1997b), strategic commitments (Sull et al. 1997), institutional constraints (Ansari and Garud 2009, Benner 2010), and customer understanding (Christensen and Bower 1996, Eggers 2014) all affect organizational adaptation to a discontinuity. One common thread among these studies is the role these constructs play in facilitating or inhibiting an organization's ability to learn about the technological discontinuity and the effect of this learning on subsequent adaptation.

In a small number of these studies, scholars observe organizations that appear to make a "half step" between generations (Ansari and Garud 2009, Benner 2010, Gilbert 2006, Tripsas 1997a, Utterback 1996), developing technology that recombines portions of the extant technology with the threatening technology to create a hybrid technology—what we label an *intergenerational hybrid*. Despite relatively limited research attention, intergenerational hybrids appear during a surprising number of technological discontinuities. The sail–steam, typewriter–PC, hot metal–photo typesetting, film–digital photography, and cellular–data network hybrids mentioned earlier are but a small sampling of intergenerational hybrids. Other examples abound, including the hybrid flash–hard disk bridging the storage and speed divide between flash memory and traditional hard drives, online backup services utilizing "snail mail" shipments of hard drives when bandwidth is limited, "bricks and clicks" business models that combine elements of "brick-and-mortar'' (physical) and Internet business models, and hybrid cloud services that combine elements of cloud- and network-based computing. In short, we argue that the frequency with which we observe hybrids between technology generations suggests that they may play an important role in technology discontinuities.

Such intergenerational hybrids are an important artifact of study because of their potential impact on organizational adaptation to technology discontinuities. Unfortunately, intergenerational hybrids have come to be viewed informally as clumsy attempts to cross from one technical paradigm to the next and, as such, represent the physical manifestation of organizational inertia. Because prior research emphasizes that an organization's existing knowledge can lead decision makers to misperceive (Henderson and Clark 1990) or underadapt to (Holbrook et al. 2000, Kaplan et al. 2003, Tripsas and Gavetti 2000) technology discontinuities, intergenerational hybrids that incorporate an organization's prior knowledge are sometimes viewed as inertial, underadaptive responses to the emerging technological paradigm (Christensen and Bower 1996, Gilbert 2005). Furthermore, because hybrids (we use the term "hybrids'' as shorthand for intergenerational hybrids) often incorporate components from an emergent technology in its infancy (Christensen 1992a, b; Foster 1986), hybrids incorporating this technology can themselves appear underdeveloped relative to the later, more mature technology.

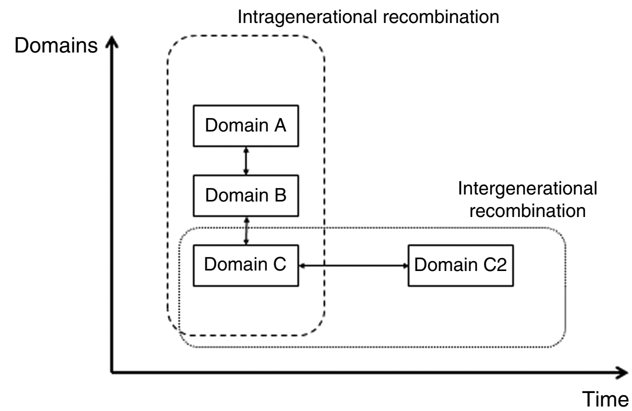
Despite these negative views, we propose a contrasting view that intergeneration recombination may, at times, act as a useful organizational response to technological uncertainty. Although many technologies often threaten an existing paradigm, these technologies may fail to materialize or may take years to overcome existing technology (Adner and Kapoor 2012, Agarwal and Bayus 2002, Anderson and Tushman 1990). Spanning such long technology transitions poses significant challenges to incumbents attempting to profit from market demand in the old technology while adapting their capabilities in the new technology. Incumbents that leap too early before a threatening technology has adequately matured may fall into a number of traps, such as concluding that the new technology has little merit (Gilbert 2005, Utterback 1996), unwittingly creating early lock-in to premature versions of a dominant design (Eggers 2014), or placing bets on the wrong technology in a technology competition (Eggers 2012). By contrast, incumbents that move too late into the new technical generation also face significant adaptation challenges, as incumbents struggle and often fail to catch up to competitors (Christensen et al. 1998, Eggers 2014, Tripsas and Gavetti 2000). For example, Dowell and Swaminathan (2000), in a study of the early bicycle industry, suggest that firms can manage these difficult transition periods by maintaining an overlap between the old and new generations. Such a strategy has the advantage of preserving resources and routines that retain market value while developing new resources and routines, although it may also face the challenges of competition between technical generations (Christensen and Bower 1996, Gilbert 2006).

An alternative adaptation strategy may be to take a half step into the next technical generation in the form of an intergenerational hybrid, which also allows the firm to learn about the new technology while maintaining some of its resources and routines in the old technology. Rather than being inertial mechanisms, we suggest that intergenerational hybrids may sometimes represent an option on an uncertain technical future (Brown and Eisenhardt 1997, Kogut and Kulatilaka 2001), not only as a "placeholder'' for the firm in the future market but, more importantly, a source of learning today. If the threatening technology disrupts the extant technology at some point in the future, then by using the hybrid to learn about the threatening technology before the discontinuity occurs, the incumbent could obtain a learning advantage in the new technology compared with incumbents that try to enter the new technology later. This learning advantage could accrue in the core technology and lead to important complementary knowledge, such as information on the market and customer preferences (Eggers 2014). Furthermore, by developing a hybrid, incumbents may also learn about the timing of the discontinuity itself, avoiding the common incumbent mistakes of leaping too early or too late into a threatening technology (Christensen et al. 1998, Taylor and Helfat 2009). If the threatening technology fails to take hold, it is true that developing an intergenerational hybrid wastes resources relative to no investment in the new technology. But the dangers of inertia in the face of a threat are clear, and taking a half step into a technology discontinuity that never materializes wastes fewer resources than leaping fully into a failing technology (Eggers 2012). Furthermore, in the process of developing an intergenerational hybrid, incumbents may find opportunities to borrow from the threatening technology to improve products in the old technology generation, perhaps giving a firm an advantage over competitors lacking such technology.

As a relevant contemporary example, consider the choices that Toyota, a manufacturer of traditional internal combustion engine (ICE) vehicles, faces with respect to the potential threat posed by electric vehicles. The threat of an electric vehicle discontinuity is uncertain but potentially disruptive. Toyota could choose to leap directly into electric vehicles, but it may take decades for electric vehicles to replace combustion vehicles, if such a discontinuity occurs at all. Alternatively, Toyota could choose to wait until an electric vehicle future emerges, at which point it may be too late to respond effectively to the new technical generation. Toyota's mixed response was to create the Prius, an intergenerational hybrid between ICE and electric vehicles that effectively provides the organization a learning option about the future. If electric vehicles emerge as the new dominant paradigm, Toyota will have developed significant knowledge and capability advantages in the new domain (e.g., sourcing and manufacture of electronic components, as well as consumer preferences) that could provide it with an advantage in making the transition to an electric vehicle future relative to its competitors who, in their inertia, fixated on the ICE automobile. Furthermore, because Toyota has been involved with the hybrid, it may be more likely as an organization to recognize the "window of opportunity" to leap into electric vehicles (Christensen et al. 1998). But if electric vehicles fail to emerge as a viable future, Toyota will have avoided the strategic misstep of investing heavily in electric vehicles, while at the same time creating a vehicle that has a significant performance advantage over existing combustion alternatives.

Intergenerational hybrids, therefore, may play an important role in the way organizations learn about and adapt to technology discontinuities. Although prior research has developed a rich body of knowledge about the recombination of contemporary elements, or intragenerational recombination (Ahuja and Katila 2001, 2004; Fleming and Sorenson 2001), relatively little research has examined

Figure 1 **Intragenerational vs. Intergenerational Knowledge Recombination**



recombination over technical generations, or intergenerational hybrids. We define intragenerational hybrids as the recombination of elements across contemporary, or parallel, technology domains, whereas we define intergenerational recombination as the combination of technology elements across competing technology generations (see Figure 1). For example, hybrid disk drives combine an extant technology generation (hard disk drive technology) with a threatening future technology (NAND solid-state drive technology, which acts as a cache for the traditional hard drive, improving its performance); other more familiar intergenerational innovations in hard disk drives borrow from contemporary technologies, such as the shift from stepper motors to voice coil actuators to move the hard disk arm.

Naturally, intergenerational hybrids are bounded both in probability and in impact. The probability of intergenerational recombination depends on the potential level of recombination across technology generations, most often in the form of modular components or in architectures that can be substituted or modified between generations (Baldwin and Clark 2000, Garud and Kumaraswamy 1995). As a result, intergenerational recombination may be (1) more likely to occur in products, especially assembled products, because they are more likely to have modular components or modifiable architectures; (2) less likely to occur in nonassembled products (although they do occur, as illustrated by the earlier examples of hybrid business models and services), and (3) unlikely to occur when technology generations have no compatibility in components or architectures. One example of a technology discontinuity where intergenerational hybrids are unlikely to occur is the shift from printed books to electronic books. This shift does not lend itself well to hybrids because there are few modular components to recombine. Similarly, in the chemicals industry, products with differing underlying compounds may not lend themselves to hybridization.

The impact of a hybrid on organizational adaptation to a discontinuity may depend on many factors,[1] most importantly the degree to which the development of a hybrid generates learning relevant to the potential future discontinuity. A hybrid may or may not generate learning relevant to a potential discontinuity for many reasons, such as if organizations (1) integrate less relevant technologies, (2) underinvest in future technologies, or (3) invest at an inappropriate time. First, if a hybrid integrates less relevant technology, such as the losing technology in a competition between technology variants of a future generation, there may be limited learning benefits. Second, underinvesting in future technologies, such as investing in a "backward-looking" hybrid that serves primarily to preserve the older technology, may limit the learning impact of a hybrid.[2] Third, investing in hybrids at an inappropriate time, such as after a discontinuity has already occurred, may limit the knowledge a firm generates from a hybrid or may even be counterproductive to adaptation.

Despite this boundary condition, and even sometimes in spite of these boundary conditions, there are many ways in which developing hybrids may still generate learning about supply, demand, or timing dynamics; such learning can impact an organization's ability to adapt to a technology discontinuity. For example, developing a hybrid using the wrong technology may be less costly than making the mistake of leaping fully into the wrong technology. As Eggers (2012) demonstrates in a study of the flat-panel display industry, organizations that took the full step into the losing technology among competing technology alternatives proved more inertial to adopting the winning technology. At the same time, even when developing a hybrid technology with the losing technology variant, an organization may still develop beneficial demand-side knowledge about customer preferences or knowledge about the timing of the transition. In support of such a view, Eggers (2014) shows that the very firms that picked the wrong technology, if they could overcome the inertia created by picking the wrong technology, actually outperformed firms that initially picked the winning technology because they had developed valuable customer and market knowledge from their experience with the losing technology.

Intergenerational Hybrids, Knowledge, and Technology Spillbacks

How investments in knowledge affect the development of hybrids remains an important but unexplored factor in understanding whether and when intergenerational hybrids operate as inertial or learning mechanisms. Although several knowledge types have been identified by prior literature (e.g., core versus integrative, operational versus inventive), inventive knowledge, such as patenting an invention, may be the most relevant to intergenerational hybrids. Such inventive capability has often been described as a higher-order capability (Moorman and Miner 1998), an architectural capability (Henderson and Cockburn 1994), or a dynamic capability (Helfat and Peteraf 2003) that increases the ability of organizations to develop new knowledge.

Whereas operational knowledge in an extant technology domain may create inertia to organizational adaptation, inventive knowledge in the existing domain may actually help facilitate the development of intergenerational hybrids. Because operational knowledge in a domain tends to be highly routinized, structured, and embedded in resources and processes (Dosi et al. 2000, Nelson and Winter 1982), such knowledge may contribute to the rigidity observed by previous scholars (Benner and Tushman 2002, 2003; Gilbert 2005; Tripsas and Gavetti 2000). By contrast, although inventing in an older technology generation could be maladaptive behavior focused on extending older technologies (Furr and Snow 2014), inventive knowledge developed in old technologies may also have some advantages. When organizations invent in an existing technological regime, they demonstrate knowledge related to developing novel insights: "higher-order" or "dynamic" knowledge that may have greater flexibility and applicability to intergenerational hybrids than more operational knowledge (Furr et al. 2012, Garud and Nayyar 1994, Helfat and Peteraf 2003). Such inventive capabilities developed in an incumbent technology may help organizations invent in future generations (Sosa 2009, 2011; Tripsas 1997a), including developing higher-performing intergenerational hybrids.

Specifically, inventive knowledge in the extant technology generation may increase the likelihood that organizational members see opportunities to develop higher-performing hybrids for several reasons. Because an organization has experience creating novel recombinations with the extant technology, it may be more likely to spot recombinations with the new technology, some of which may be higher performing. Or it may be more likely to see opportunities to improve an intergenerational hybrid than organizations lacking such inventive knowledge. Hence, greater inventive knowledge, even if it is in the extant technology, may increase the ability of an incumbent to recognize valuable elements of a future technology generation and integrate these elements into extant technology in the form of a higher-performing intergenerational hybrid.

Hypothesis 1. *The greater an organization's inventive experience with the extant technology, the greater the performance of its intergenerational hybrid technology.*

In addition to inventive knowledge in the old technology, inventive knowledge in the new technology may contribute to the development and performance of intergenerational hybrids. Organizations often invest in a threatening technical domain before entry into that domain (Cattani 2005, Eggers 2014). These investments may help organizations later to cross into the new technical domain (Eggers and Kaplan 2009), but before that time, investments in developing knowledge about a new domain may contribute to the development of intergenerational hybrids (Brusoni et al. 2001, Pisano 1996). Specifically, organizations learn new skills by recombining their current capabilities (Kogut and Zander 1992), and if organizations develop intimate knowledge about a new technology domain, organization members are more likely to recognize new knowledge that could be recombined with their existing knowledge (Helfat and Raubitschek 2000). These novel components could be integrated with existing technology to increase the performance of extant products—a spillback from the novel technology to the current generation.

We define *spillbacks* as the spillover of knowledge from a threatening technology generation to the extant technology regime. In the context of a technology discontinuity, spillbacks may occur when organizations borrow elements from a threatening technology generation that could improve the performance of the focal generation. Such spillbacks can contribute to performance improvement for the focal firm or for the technology generally. For example, when threatened by Thomas Edison's light bulb, gas lighting incumbents borrowed the idea of the filament to increase the efficiency of gas lighting fivefold—an improvement that threatened to destroy the nascent electric lighting industry and, in turn, rendered it difficult for Edison to commercialize electric lighting (it took 12 years to turn a profit) (Utterback 1996).

As an example in the context of this study, when EFI emerged in the 1980s as a competitive threat to carburetors, it was not clear whether it would really displace the carburetor. The carburetor had been the primary method for delivering gasoline to an engine almost since the emergence of the automobile a century earlier. Carburetors had already been threatened by competing technologies that had failed to overtake the carburetor (wick carburetors, the rotating brush carburetor, catalytic carburetors, vaporizers, and mechanical fuel injection, among others). When EFI emerged, it was unclear whether the delicate electronics of early EFI products could survive in the harsh environment of the passenger vehicle or if the expensive components would become affordable for mainstream vehicles. Although some firms began to invest significantly to research and patent in the new technology, others invested less. Part of EFI technology included electronic fuel controls, which could be borrowed and integrated into the extant carburetor architecture to create a hybrid with the potential to improve the performance of the standard carburetor. At the time, carburetors were still being demanded widely in the market, but as EFI began to encroach on the higher-end market segments, most incumbents developed hybrid carburetors that combined electronic controls and the carburetor architecture. Among their attempts to develop hybrids, incumbents investing in understanding the new EFI technology should have been more likely to capture spillbacks in the form of intergenerational hybrids because they had developed greater knowledge about the new technology (which could be recombined) than those incumbents who did not invest.

More generally, organizations with greater inventive knowledge developed in the threatening technology may be more likely to see elements of the future technology that could be recombined with the extant technology or to see opportunities to improve an intergenerational hybrid than organizations lacking such knowledge. Therefore, we predict that organizations with greater inventive experience in the threatening technology may have a greater likelihood of recognizing components from a threatening technology and understanding how to integrate these components to capture spillbacks that improve the performance of intergenerational hybrids.

Hypothesis 2. *The greater an organization's inventive experience with the threatening technology, the greater the performance of its intergenerational hybrid technology.*

Finally, in addition to inventive knowledge in the threatening technology domain, it may be the case that some organizations have related inventive knowledge capabilities that could impact the development and performance of a hybrid. With practice, organizations increase their ability to recombine knowledge (Grant 1996, Kogut and Zander 1992), and organizations with experience inventing in an area related to the focal domain may have developed generalized inventive experience (e.g., experience with the knowledge creation process) or related inventive experience (e.g., knowledge related in some way to the focal area) that increases their likelihood of recombining knowledge in the focal domain (Helfat and Raubitschek 2000). As evidence of this possibility, in her study of the petroleum industry, Helfat (1997) finds that organizations investing in petroleum refining research and development were more likely to invest in complementary knowledge development in related areas, such as coal gasification. It follows that if organizations have developed inventive capabilities in related technical areas, they may have developed learning and recombination capabilities that could positively impact their ability to develop high-performing intergenerational hybrids (Helfat and Raubitschek 2000, Kogut and Zander 1992). Because these inventive organizations have practice at recombining knowledge related to the focal domain, they may be more likely to recognize opportunities to recombine old and new technologies and see more opportunities to improve the performance of an intergenerational hybrid.

Hypothesis 3. *The greater an organization's related inventive experience, the greater the performance of its intergenerational hybrid technology.*

Intergenerational Hybrids and Technology Spillforwards

Earlier we emphasized the many challenges incumbents face when adapting to technology discontinuities

(Eggers 2012, Gilbert 2005, Taylor and Helfat 2009). In particular, incumbent organizations often struggle to develop knowledge about the new technology because they are reluctant to fully adopt uncertain, threatening technologies prematurely. Sometimes the reasons are inertial and sometimes they are appropriate—relating to the uncertainty inherent in whether a technology transition will occur (Furr and Snow 2014, Wu et al. 2014). Given the organizational and political challenges of taking the full step into an uncertain, threatening technology, an organization may be more willing to take a half step in the form of an intergenerational hybrid. Although not fully adopting the technology, such a half step may help the organization learn about and adapt to tomorrow's technology in today's time frame rather than when the discontinuity has already destroyed an incumbent's advantage. There are several types of knowledge that organizations may accumulate by developing hybrids, particularly higher-performing hybrids. These include supply-side, demand-side, and timing knowledge.

First, producing an intergenerational hybrid may offer an opportunity for organizations to develop supply-side knowledge and capabilities related to the technology uncertainty that could be beneficial in later adaptation. By developing a hybrid that incorporates elements of a threatening technology, organizations can develop valuable knowledge about the technology itself, particularly its features and capabilities, as well as how to effectively design and develop the new technology. Furthermore, producing a hybrid provides an organization the opportunity to develop knowledge about the production process, which, in turn, could allow an incumbent to start moving down the learning curve in the new technology as well as start to capture increasing marginal returns to scale in the new technology. In our Toyota hybrid example, by producing the hybrid, Toyota has developed knowledge about technology itself (e.g., electric drivetrains, batteries, systems), how to produce the technology (e.g., how to design systems, source components, manufacture systems), and early production benefits (e.g., moving down the learning curve in electric components and moving closer to economies of scale in electrical components and systems). Although such supply-side knowledge has value in resolving the technical uncertainty and facilitating adaptation to a threatening discontinuity, organizations are likely to make different levels of investment in hybrids, thereby reaping different amounts of knowledge relevant to future adaptation efforts. Incumbents that underinvest in hybrids by, for example, grafting outsourced components from the threatening technology or hastily developing poorly performing hybrids likely develop very limited knowledge and few learning-curve or economy-of-scale benefits that could be useful in future adaptation efforts. By contrast, organizations that make greater investments in the new technology and how to integrate it into a hybrid are more likely to capture such potential benefits. Furthermore, by better integrating the technology into a hybrid, such organizations may actually develop greater knowledge that has a dynamic, architectural component that could be valuable in future adaptation (Helfat and Peteraf 2003, Henderson and Cockburn 1994).

Second, producing an intergenerational hybrid may allow organizations to develop demand-side knowledge valuable to adaptation or even to favorably shape demand itself. By developing a hybrid that incorporates elements of a threatening technology, organizations can begin to develop knowledge about the demand uncertainty they face, such as how customers react to the new technology, how they like to employ the technology, how to market the technology, and so forth. Furthermore, organizations may have the opportunity to influence demand itself, potentially shaping how customers interpret the technology or how they adopt the technology. In our Toyota example, by developing the hybrid, Toyota has learned about how to market, distribute, and sell vehicles with electric components to customers, but it has also shaped customer interpretations of vehicles with electric components. As another illustration, in his work on the flat-panel display industry, Eggers (2014) highlights that incumbents who developed the losing technology in a discontinuity still developed valuable demand-side knowledge about customer preferences; this helped them adapt to the discontinuity. Although they have the opportunity to develop such valuable demand-side knowledge by developing a hybrid, if organizations underinvest and create an underperforming hybrid, they may not capture such valuable knowledge. In the worst case, if an incumbent launches a hybrid that has inferior capabilities, the incumbent may actually reap counterproductive demand-side knowledge if customers fail to use the hybrid (e.g., the lessons learned about demand may be lower with lower sales, or the incumbent may conclude that customers do not want the new technology when, in fact, the flaw lies in the hybrid itself). By contrast, organizations that can overcome the base performance threshold for a hybrid to be accepted or develop higher-performing hybrids are more likely to generate more demand-side knowledge that could be valuable in future adaptation.

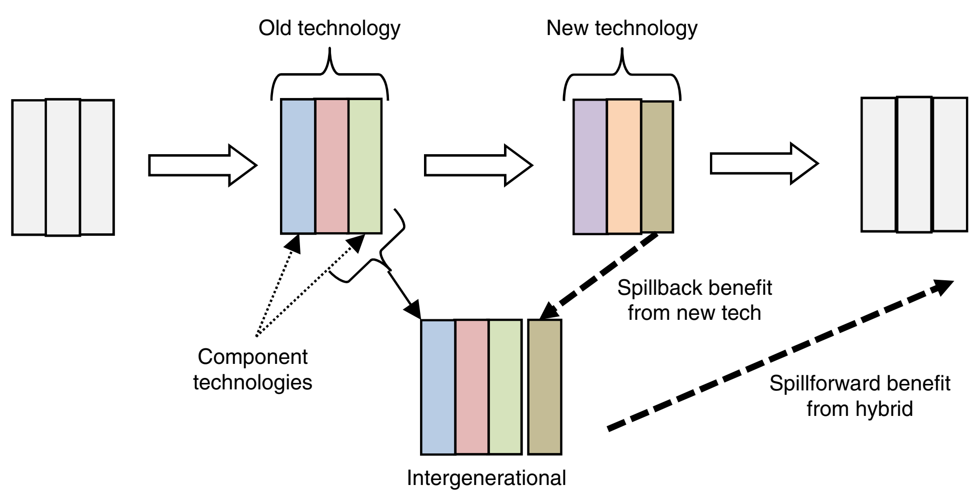
Third, in addition to helping an organization develop supply- and demand-side knowledge related to the new technology, a hybrid may help the organization develop knowledge about how to better time a transition into the new generation. Correctly timing adaptation during a technological discontinuity can be critical to successful adaptation (Anderson and Tushman 1990, Suárez and Utterback 1995). We have already discussed the challenges identified in the literature from moving too early or too late into new technologies. Christensen et al. (1998) suggest that the optimal time for incumbents to enter a new technology industry is not during the early era of ferment but during the window of opportunity immediately before a dominant design emerges. By integrating two technology regimes in the form of an intergenerational hybrid, an organization may gain insight into the timing of a discontinuity and thereby avoid leaping into a technology prematurely. Alternatively, as organizations develop hybrids, they may be able to more effectively wait out the competition between technology variants for the dominant design and then choose to enter the new technology at a more optimal moment as the uncertainty resolves.

Finally, organizations that have developed hybrids may be able to better influence the competitive or institutional environment in such a way as to influence the timing of the technology discontinuity itself (Furr and Snow 2014). Whereas all incumbents developing hybrids may generate timing knowledge, organizations that have developed higher-performing hybrids are likely to have greater insight and influence on the technology discontinuity itself. For example, massive online open courses (MOOCs) offered by traditional universities could be considered a hybrid between traditional universities and a future technology (fully online, open universities) because they combine components of current technology (e.g., professors, content, format of a traditional course) with a future technology (e.g., Internet platform, social evaluation). Although all universities developing MOOCs may develop timing knowledge, our theory would predict that those universities with higher-performing MOOCs[3] are more likely to have insight into the appropriate timing of a discontinuity and greater influence on when it occurs.

In summary, developing a higher-performing intergenerational hybrid could provide significant positive learning benefits, or spillforwards. *Spillforwards* are the potential knowledge benefits from creating an intergenerational hybrid, such as knowledge of the threatening technology, discontinuity timing, or customer preferences that may spill forward into a future technological regime and potentially aid organizations in their efforts to adapt to a technology discontinuity (see Figure 2). As an additional example of such spillforwards, when the electric typewriter industry was threatened by personal computers, rather than leaping directly into personal computers, several important incumbents in electric typewriters, including IBM and Olivetti, created hybrid devices called word processors that combined electric typewriter components with the monitors, disk drives, and other familiar components of the future personal computer. If these incumbents had leapt directly into personal computers, they might have been disenchanted with lackluster sales—it took many years for the industry to transition from electric typewriters to personal computers. But once the personal computer industry did appear to be emerging, IBM and Olivetti shifted from their hybrids and entered the PC industry in a manner that defined the dominant design of the industry (Utterback 1996). Note that the roles of the typewriter, the correcting typewriter, and the hybrid word processor are glaring in their absence from existing scholarly and popular narratives surrounding IBM's "self-disruption" of its mainframe business with the PC (Christensen 1997). However, such hybrids likely helped IBM and Olivetti develop supply, demand, and timing knowledge that had value in their adaptation efforts.

Although we cannot argue that all hybrids will yield spillforward benefits, when organizations have made investments in forward-looking hybrids, they may reap spillforward benefits that could help them adapt in the future generation. Such investments may be reflected in the fact that an organization creates a hybrid technology in the first place, but they should be more strongly reflected in the performance of the hybrid itself, particularly when comparing the variance in the technical or market performance of competitors' hybrids. Although performance can be an imperfect indicator of firm investment and capabilities, among a group of competitors producing a particular type of hybrid, higher-performing hybrids are likely to be correlated with the kinds of investments and resulting knowledge hypothesized earlier. In turn,

Figure 2 (Color online) Representation of a Spillback and Spillforward



such high-performing hybrids, because they reflect greater levels of knowledge and capability development related to the new technology, should increase the likelihood of capturing spillforward benefits. Because organizations can use the knowledge and capabilities acquired while developing the hybrid to develop technologies in the new generation, they may have greater chances of successfully adapting to the next technology generation than if they lacked such knowledge and capabilities. Hence, organizations with high-performing intergenerational hybrids, as a reflection of knowledge developed, may capture spillforward benefits that may be manifest as performance advantages after a technology discontinuity.

Hypothesis 4. *The greater an organization's intergenerational hybrid performance, the greater its product performance in the new technology relative to other incumbents.*

Empirical Content and Methodology

The context of our study is a technology discontinuity in automobile fuel delivery systems that occurred during the 1980s. In the early 1980s, in response to tightening government regulation as well as consumer demand, automobile manufacturers and their suppliers introduced a potential direct substitute, electronic fuel injection, for the existing fuel delivery technology, the carburetor. From the advent of the internal combustion engine automobile through the early 1980s, the carburetor represented the dominant design in fuel delivery technology. It relied on simple mechanical valves and the Bernoulli principle to draw correct quantities of gasoline into the stream of air entering the engine. Increasingly stringent regulations on fuel economy and emissions performance placed pressure on carburetor manufacturers to create offerings that could more precisely meter gasoline and intake air.[4] Furthermore, increasing gas prices and awareness of pollution meant that customers were willing to pay for better performance (Kahn 1986). It was into this competitive landscape that EFI emerged as a threatening substitute for carburetors. EFI used electronic sensors and valves to measure and precisely meter gasoline, in theory allowing for much more precise and efficient operation. At first, the threat of EFI replacing the carburetor appeared uncertain, since it was unclear whether the expensive and delicate EFI components would be viable in a standard passenger vehicle. However, as EFI started to be adopted in certain distant market niches (e.g., expensive, high-performance vehicles), carburetor manufacturers began to adapt EFI's electronic sensors and controls for use in standard carburetors. The resulting hybrid carburetor, incorporating electronic controls, survived alongside standard carburetors and EFI through the late 1980s. By 1992, EFI achieved dominance and replaced both the standard and the hybrid carburetor.[5]

This industry is an appropriate setting in which to study the question of intergenerational hybrids and adaptation because we can observe the performance outcomes of knowledge investments and technology choices among the population of incumbents. Because of the regulated nature of the market, we can observe the full population of car models tested by the U.S. Environmental Protection Agency (EPA) ($n = 4{,}374$) from 1978 through 1992 (the entire period covering the transition from carburetors to EFI in the U.S. market). Furthermore, during this period, all carburetor firms produced carburetors but also offered a version of an intergenerational hybrid, the electronic carburetor. Although the sample is restricted to cars sold in the United States, it does include a large number of car models built by European and Asian carmakers and their carburetor suppliers.[6] Because incumbents were engaged in inventive activity in both carburetors and EFI, we can observe how differing patterns of inventive activity and differing technology choices affected product performance in the old, hybrid, and new technologies.

The base unit of observation is a car model, which is defined as any available combination of model name, body type, engine size, transmission type, power output, and carburetor type (electronic or standard). The data contain results from EPA tests of each car model's physical attributes and tested performance. We then used carburetor repair manuals to identify the carburetor manufacturer for 3,026 of the 4,374 car models in the EPA data. The 1,348 unmatched car models result from cases in which there is not a unique carburetor for a given model and from cases in which the car model does not appear in our repair manuals. The former group is largely made up of American automobile models, and the second is made up of low-volume models. In most years, the groups are statistically indistinguishable from one another. Even so, the empirical tests include firm fixed effects to help ensure that these exclusions do not bias the results. Patent data to calculate measures of carburetor firm inventive activity come from the National Bureau of Economic Research (NBER) and Harvard University (Hall et al. 2001, Lai et al. 2011).

Variable Definitions

Dependent Variable: Miles per Gallon

The dependent variable is the fuel consumption, measured in miles per gallon (*MPG*), obtained by a focal car model, as measured by the EPA. This fuel consumption is used to measure the performance of the car model's carburetor through its theoretically relevant attributes described below. In terms of relevance, *MPG* represents the critical carburetor/EFI performance metric that manufacturers strove to improve upon during this period. Fuel consumption, especially during the period of this technology transition, has been an economically significant dimension of an automobile's performance. Marginal improvements in fuel consumption have been found to command a sales price premium from customers (Kahn 1986), and inferior performance is punished by fines from government regulators under the U.S. Corporate Average Fuel Economy program.[7] During the 1970s and 1980s, increasingly restrictive federal fuel economy standards and rising fuel prices combined to make *MPG* an especially salient measure of product performance.

Independent Variables

Patents. To test Hypotheses 1–3 regarding the contribution of different types of inventive knowledge to spillbacks in hybrid performance, we construct measures based on patent data in the extant technology (carburetors) and the new technology (EFI), as well as one measuring inventive experience in a plausibly related field, semiconductors. We construct a measure, *Patents* (and its subcategorized versions *CarbPatents*, *EFIPatents,* and *ChipPatents*), that is the citation-weighted patenting activity associated with each individual car model's carburetor. Each *Patents* variable is constructed by associating individual automobile carburetors with patents that relate to the carburetor's technology. To do this, we identify the manufacturer of each carburetor in the sample. Carburetor manufacturers are then associated with patents through string searches in the "Assignee" field in the NBER patent citation file, verified by manual checks for false (negative and positive) matches. In the U.S. 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.[8]

The *Patents* measure for an individual carburetor produced by firm j in a given year t is

$$Patents_{jt}=\left(\left(\sum_{s=0}^{5}\sum_{k}\Big[1(pat\_k\_applied\_for\_in\_year\_t-s)\cdot\sum_{r=1}^{5}(count\_of\_cites\_of\_pat\_k\_in\_year\_t-s+r)\Big]\right)(100)^{-1}\right).$$

For example, the inventive activity and knowledge embodied in the Hitachi carburetor housed in a 1983 Mazda GLC is measured by patents successfully applied for (i.e., subsequently granted) by Hitachi from 1978 through 1982. The patent's application date—rather than the grant date—is used to avoid the potential problem of patent latency times changing over the sample window for bureaucratic and legal reasons outside the firm's control. New car component development begins three to seven years before launch, so the $t-s$ counter captures this lag by counting patenting activity in the five years before the carburetor's sale to the public. Because there is significant variation in the value and knowledge content of the different patents associated with individual carburetors, we follow standard practice (e.g., Hall et al. 2005, Hsu and Lim 2014, Trajtenberg 1990) and weight each patent for importance by counting the number of patents (granted to any inventor, inside or outside the carburetor firm) that subsequently cite it in the five years $(t-s+r)$ following its granting. The citation-weighted patent count is divided by 100 to make the regression coefficients more readable.

The *Patents* measure is calculated for a given carburetor (through its manufacturer and model year) across three technology areas—standard carburetors, EFI, and semiconductors (*CarbPatents*, *EFIPatents*, and *ChipPatents*, respectively)—using patent classes defined by the World Intellectual Property Organization's International Patent Classification (IPC) system. From 1970 through 1999, the U.S. Patent and Trademark Office issued 9,506 patents in the IPC classification entitled "Supplying combustion engines in general with combustible mixtures or constituents thereof." Of those 9,506 patents, 1,844 are specific to carburetors and 887 are specific to EFI. In carburetors, there are 274 assignees.

For the measure of related inventive experience, we chose semiconductor patents (*ChipPatents*), a plausibly related technology domain, as a proxy for experience that is related to the focal technology but not directly required to produce EFI. The semiconductors category is a better representation of related inventive knowledge than other candidate technology categories (e.g., composite materials, robotics, user interfaces) because it is related to EFI (generic semiconductors are a component of EFI systems) and because it is comparable across all firms (all firms patented in semiconductors). We chose a related technology category over more general measures such as all patents because the variation in firm diversification decreases the comparability of firms with different portfolios of patenting activity when such portfolios include potentially irrelevant patenting areas (e.g., satellites patented by Ford and bicycles by Hitachi).

To separate out the effect of inventive activity on hybrids from standard carburetors, we interact the binary variable *Hybrid*, which is equal to 1 when the car has a hybrid carburetor and 0 when it has a standard carburetor, with the patent measure. Patents' shortcomings as measures of inventive activity and knowledge are well documented, yet patents remain helpful measures of these constructs in large cross-sectional studies, especially when they are properly weighted (Trajtenberg 1990).

HybridPerf and StandardPerf. To test Hypothesis 4 (that the greater performance of a firm's hybrid carburetors will lead to subsequent improved performance in EFI), we construct *HybridPerf* and *StandardPerf*, measures of the performance of a firm's hybrid and standard carburetors, respectively. For these measures, we use the STATA postestimation command "predict" following the pooled specification from the tests of Hypotheses 1–3 (reported in Model 1 of Table 2) to generate expected values of *MPG* for each individual carburetor model in the sample given its observable attributes. This predicted value is then subtracted from the carburetor's actual measured *MPG*, creating a measure of a carburetor's over- or underperformance given its observable attributes. These over- or underperformance values are averaged over model year by carburetor type (e.g., *Hybrid* or not) and interacted with manufacturer (i.e., carburetor type × carburetor manufacturer). The difference between these values provides a firm-level measure of the annual under- or overperformance of a firm's hybrid and standard carburetors relative to those of its competitors. These values are calculated for a range of lags (1 through 4 years: $HybridPerf_{t-1}$ through $HybridPerf_{t-4}$) for use in predicting subsequent *MPG* performance for the firm's EFI offerings. For example, consider the 1989 Toyota Camry. Its EFI system was produced by the firm Aisan, a supplier that had also supplied hybrid carburetors before making the transition to EFI. The measure of $HybridPerf_{t-1}$ for the 1989 Camry's Aisan EFI system represents the extent to which hybrid carburetors produced by Aisan in 1988 over- or underperformed relative to hybrid carburetors produced by other carburetor firms in 1988. To test Hypothesis 4, we then use this *HybridPerf* value to predict the performance of a firm's EFI system as a proxy for a firm's learning acquired in executing the hybridization of the old and new technologies, relative to its competitors. Similarly, the *StandardPerf* measure proxies the level of a firm's learning acquired in extracting performance from the existing technology.

Control Variables

To control for all other factors that could affect *MPG*, we construct a vector of observable attributes for each car model, including model year (*ModelYear*); measured curb weight (*Tons*); engine's displacement, a measure of the size of the engine, in liters (*Liters*); automatic or manual transmission (*Autotrans*); and power output (*Horsepower*). Table 1 provides summary statistics. The results are robust to the alternative controls that we tested, but that reduced the sample size.

Estimation

For Hypotheses 1–3, we estimate the individual and joint (interacted) impact of the different types of firm carburetor knowledge and inventive experience (*Patents*) and of the *Hybrid* technology on the fuel economy (*MPG*) of an individual carburetor, as estimated though the attribute-controlled fuel economy performance of the car model in which it is housed. To test Hypotheses 1–3, we begin with the base ordinary least squares (OLS) specification:

$$\begin{aligned} MPG_i = {} & \alpha_1 + \beta_1(Hybrid)_i + \beta_2(CarbPatents)_i \\ & + \beta_3(Hybrid \times CarbPatents)_i \\ & + \beta_4(EFIPatents)_i \\ & + \beta_5(Hybrid \times EFIPatents)_i \\ & + \beta_6(ChipPatents)_i \\ & + \beta_7(Hybrid \times ChipPatents)_i + \beta_8(Tons)_i \\ & + \beta_9(Liters)_i + \beta_{10}(Autotrans)_i \\ & + \beta_{11}(Horsepower)_i + e_i, \end{aligned}$$

in which the fuel economy *MPG* of car model i is regressed on its carburetor technology ($Hybrid = [0, 1]$), its attributes (weight (*Tons*), engine displacement size (*Liters*), transmission type ($Autotrans = [0, 1]$), and power (*Horsepower*)), and patents granted to its carburetor's source firm (*Patents*). The carburetor firm patent variables are interacted with a dummy variable, *Hybrid* (taking a value of 1 where model i contains a hybrid carburetor and 0 where it contains a standard carburetor), to tease out the relationship between knowledge and performance of the two carburetor types. We also estimate this regression model in samples restricted to standard or hybrid carburetors, effectively removing the hybrid interactions and therefore simplifying interpretation. In all of the regressions, the continuous measure of *MPG* is explained using continuous and categorical variables describing the carburetor, the car model in which it is housed, and the firm knowledge associated with it. Robust standard errors are clustered at the carburetor firm level to control for potential bias from autocorrelation (Bertrand et al. 2004).

To address potential endogeneity and unobserved variable concerns, we include firm, year, and car class fixed effects in the regressions. Inclusion of these fixed effects means that the estimated results come from within-firm

Table 1 Descriptive Statistics and Pairwise Correlation for Variables Used in the Regression Analysis

Variable	Mean	Std. dev.	Min	Max	1	2	3	4	5	6	7	8
1 *MPG*	23.4	7.7	10.1	59.4								
2 *CarbPatents*	0.53	0.40	0.00	1.30	−0.37							
3 *EFIPatents*	0.18	0.25	0.00	1.07	−0.07	0.31						
4 *ChipPatents*	1.49	3.92	0.00	38.59	0.29	0.08	0.26					
5 *Hybrid* (categorical)	0.41	—	—	—	0.29	−0.22	0.17	0.13				
6 *Tons*	1.8	0.45	0.88	2.98	−0.88	0.36	0.16	−0.27	−0.23			
7 *Liters*	3.55	1.55	0.99	6.96	−0.85	0.42	0.11	−0.29	−0.20	0.91		
8 *Autotrans* (categorical)	0.51	—	—	—	−0.33	0.17	0.09	−0.13	0.01	0.25	0.29	
9 *Horsepower*	114	34	46	235	−0.80	0.40	0.23	−0.26	−0.17	0.83	0.90	0.28

and within-firm/within-category variation. Furthermore, because the relationship between the patent-based experience measures and *MPG* may be nonlinear, we include quadratic terms for the *Patents* variables. To test Hypothesis 4, we use OLS to estimate the impact of *HybridPerf* and *StandardPerf* on the subsequent performance of a firm's EFI-equipped car models. To address the potential criticism that unobserved firm characteristics could be acting both on product performance and on patenting activity (leading to biased estimates of the effect of patenting on carburetor *MPG*), we include carburetor firm (*Carbco*) fixed effects. In addition, if the rate of improvement in carburetors is nonlinear over time, then the inclusion of a linear model year term measuring annual improvement in carburetor efficiency could introduce bias. To address this concern, we include model year fixed effects. Finally, there could be attributes of carburetor models that cause them to be more or less suited to the addition of hybrid technology. If these attributes were unobserved by the researcher but observable to automobile and carburetor firms, then this could bias our estimates. Based on the assumption that these attributes should be correlated with the class of car model (compact, sports car, station wagon, etc.; hereafter referred to as *CarClass*) in which a carburetor is fitted, we include fixed effects that are interactions between *CarClass* and carburetor firm (*Carbco*). As a robustness check for Hypothesis 3, we report regression results in Table 3, excluding one outlier firm that seems to be driving such results.

The inclusion of firm, car class, and year fixed effects addresses another potential source of bias in the form of unobserved variables. Among possible explanations for the changes we observe in *MPG* are factors such as firm age, firm governance structure, macroeconomic factors, government regulation, and firm nationality. Our fixed effects specifications examine variation within firm, within car class, and within year. This significantly reduces the likelihood that the results we observe are being driven by unobserved variation in factors outside the scope of our study.

Table 2 **OLS Estimation of Inventive Activity's Effect on *MPG* for Hybrid and Standard Carburetors**

	Model 1: Pooled sample	Model 2: Standard carburetors	Model 3: Hybrid carburetors
Hybrid	2.400*		
	(1.270)		
CarbPatents	5.689**	7.684**	−2.188
	(2.455)	(3.263)	(2.715)
Hybrid × *CarbPatents*	−3.220		
	(3.573)		
CarbPatents^2	−1.104	−2.840	1.994
	(2.100)	−2.372	(1.753)
Hybrid × *CarbPatents*^{2}	0.239		
	(2.726)		
EFIPatents	−7.003*	−9.601**	−7.339*
	(3.749)	(3.913)	(3.571)
Hybrid × *EFIPatents*	6.929		
	(4.739)		
EFIPatents^2	4.491	5.434	7.123**
	(3.797)	(3.174)	(2.397)
Hybrid × *EFIPatents*^{2}	−4.080		
	(4.950)		
ChipPatents	0.964***	−1.064**	0.358**
	(0.286)	(0.403)	(0.115)
Hybrid × *ChipPatents*	−0.639**		
	(0.214)		
ChipPatents^2	−0.0641***	0.0158	−0.00782**
	(0.0130)	(0.0150)	(0.00256)
Hybrid × *ChipPatents*^{2}	0.0560***		
	(0.0123)		
Tons	−9.200***	−7.137***	−14.05**
	(2.702)	(1.505)	(5.150)
Liters	−0.528	−0.748**	−0.105
	(0.351)	(0.256)	(0.586)
Autotrans	−2.015***	−1.704**	−2.316***
	(0.580)	(0.592)	(0.425)
Horsepower	−0.0462***	−0.0316***	−0.0551**
	(0.0127)	(0.00532)	(0.0177)
Constant	34.95***	33.85***	49.78***
	(3.651)	(2.360)	(8.094)
Fixed effects	*Carbco* × *CarClass*, *ModelYear*	*Carbco* × *CarClass*, *ModelYear*	*Carbco* × *CarClass*, *ModelYear*
Observations	3,026	1,789	1,237
R-squared	0.546	0.558	0.471

Notes. The dependent variable is *MPG*. Robust standard errors in parentheses are clustered by carburetor firm.
*Significant at 10%; **significant at 5%; ***significant at 1%.

Results

Table 1 reports summary statistics and pairwise correlations. To test Hypothesis 1, we examine whether inventive knowledge in the old technology, carburetors, improves the performance a firm may extract from its hybrid offering. Accordingly, the coefficient estimate of the interaction between carburetor-related patenting *CarbPatents* and *Hybrid* should be positive and significant. Results reported in the base specification in Table 2, Model 1 do not support this. As a firm's level of carburetor-related patenting increases, there is no statistically significant impact on its *Hybrid* performance (i.e., *Hybrid* × *CarbPatents* is not significantly different from *CarbPatents*). In the same regression restricted to a sample containing only hybrid carburetors (see Table 2, Model 3), the coefficient estimate on *CarbPatents* is also not significant. Although these results do not support Hypothesis 1, we note that carburetor patenting does have a positive and significant impact on the performance of a firm's standard carburetors. Though not among our hypothesized effects, this estimate lends credibility to the results because one would expect that patenting in standard carburetors leads to increased performance in standard carburetors.

Hypothesis 2 argued that inventive knowledge in the new technology should improve hybrid performance. Models 1–3 in Table 2 show a curvilinear relationship. Although the direct effect of EFI patents on hybrid performance appears neutral or negative (*Hybrid* × *EFIPatents* in Model 1 has no effect, and *EFIPatents* in Model 3 is negative and significant), the coefficient estimate on the quadratic term $EFIPatents^2$ in Model 3 is positive, significant, and relatively large (*EFIPatents* is −7.339 and $EFIPatents^2$ is 7.123). The relationship between EFI patenting and *MPG* inflects from negative to positive at an *EFIPatents* value of 0.56. Referring to the descriptive statistics for *EFIPatents* in Table 1, this is approximately 1.3 standard deviations above the mean patents, a finding solidly reflected in the descriptive data. In other words, greater citation-weighted EFI patents improve hybrid carburetor performance, but only for firms making greater investments in EFI patents. This is consistent with the idea that underinvestment in future technology could be unproductive or counterproductive and may provide insight into why some hybrids seem to be counterproductive for some organizations and productive for others. These results provide nuanced confirmatory evidence for Hypothesis 2. Note that the estimates of the effects of *EFIPatents* interacted with *Hybrid* provide further indirect evidence that the EFI patent results are not driven by unobserved firm characteristics that might increase product efficiency or the likelihood to patent: such unobserved variation in firm resources would likely cause EFI and carburetor patenting to have the same sign. These results suggest that inventive experience in the new technology is important to the successful adaptation of components from the new technology for use in extant technology products.

To test Hypothesis 3, a prediction that related inventive experience improves hybrid performance, we estimate the effect of firm inventive experience in an advanced technology only indirectly related to carburetors. The results reported in Tables 2 and 3 provide mixed evidence, mostly failing to provide support for Hypothesis 3. In Table 2, Model 1, the calculated effect of semiconductor *ChipPatents* on *Hybrid* carburetors (*Hybrid* + *Hybrid* × *ChipPatents*) is not significantly different from zero. Model 3 reports results of a regression restricted to *Hybrid* carburetors only. In this regression, the coefficient on *ChipPatents* is positive and significant, with a negative estimate of $ChipPatents^2$ indicating a positive but diminishing effect of semiconductor knowledge on hybrid performance. In robustness checks, this effect appears to be driven largely by one outlier firm, Hitachi (which has more than 10 times the number of citation-weighted patents in semiconductors as the next firm, Ford). We replicate the Table 2 results without Hitachi in Table 3, Models 4–6, and find that the relationship between *ChipPatents* and hybrid performance disappears entirely.

Table 3 Robustness Check of OLS Estimation of Inventive Activity's Effect on *MPG* for Hybrid and Standard Carburetors (Excluding Hitachi)

	Model 4: Pooled sample	Model 5: Standard carburetors	Model 6: Hybrid carburetors
Hybrid	9.414*** (1.199)		
CarbPatents	7.010*** (2.031)	9.407** (3.414)	0.550 (1.470)
Hybrid × *CarbPatents*	−1.370 (2.801)		
$CarbPatents^2$	−1.652 (2.075)	−4.096 (2.430)	1.084 (0.825)
Hybrid × $CarbPatents^2$	−0.980 (2.348)		
EFIPatents	−6.472* (3.182)	−10.11** (4.138)	−10.04** (3.850)
Hybrid × *EFIPatents*	2.692 (4.665)		
$EFIPatents^2$	3.557 (3.185)	4.752 (3.518)	9.385** (3.695)
Hybrid × $EFIPatents^2$	−1.312 (3.989)		
ChipPatents	5.409 (4.697)	0.809 (4.195)	6.365 (4.717)
Hybrid × *ChipPatents*	0.523 (3.026)		
$ChipPatents^2$	−2.196 (2.095)	−0.517 (2.183)	−1.928 (1.861)
Hybrid × $ChipPatents^2$	0.760 (1.687)		
Tons	−7.906*** (1.915)	−6.750*** (1.360)	−11.31** (3.550)
Liters	−0.724** (0.264)	−0.903*** (0.181)	−0.313 (0.521)
Autotrans	−1.724** (0.532)	−1.430** (0.507)	−2.086*** (0.463)
Horsepower	−0.0428*** (0.0124)	−0.0316*** (0.00624)	−0.0501** (0.0180)
Constant	32.14*** (2.095)	32.12*** (3.004)	42.54*** (4.860)
Fixed effects	*Carbco* × *CarClass*, *ModelYear*	*Carbco* × *CarClass*, *ModelYear*	*Carbco* × *CarClass*, *ModelYear*
Observations	2,704	1,636	1,068
R-squared	0.598	0.579	0.529

Notes. The dependent variable is *MPG*. Robust standard errors in parentheses are clustered by carburetor firm.
*Significant at 10%; **significant at 5%; ***significant at 1%.

In Hypothesis 4, we predict that a firm's superior hybrid performance correlates with the development of knowledge that may lead to superior subsequent performance in the future technical generation—a spillforward effect. To test for potential spillforwards, we created a series of variables, *HybridPerf* and *StandardPerf,* to measure the effect of a manufacturer's hybrid carburetor performance on the average annual over- or underperformance of a firm's EFI (i.e., new technology) offerings relative to the expected average performance. Relative EFI performance (to competitor firms) is a better measure of technological outcomes than is absolute EFI performance because it controls for variation (e.g., gas prices, government regulation) that might cause industry-wide increases or decreases in EFI performance. We regress the *MPG* of EFI-equipped car models on these variables and on a set of controls identical to those found in Model 1 in Table 2. In Models 7–10 in Table 4, a firm's previous over- or underperformance in hybrids is modeled as predicting performance in its EFI offerings one, two, three, and four years later. Models 8 and 9 suggest that high-performing hybrids result in greater performance, relative to competitors, in the later EFI generation. Specifically, over- and underperformance in hybrid carburetors does not seem to have a short-term effect (i.e., $HybridPerf_{t-1}$ is not significant in Model 7), and its effect is attenuated with time (i.e., $HybridPerf_{t-4}$ is not significant in Model 10). A firm's overperformance in standard carburetors (*StandardPerf*) does not significantly help or hurt subsequent EFI

Table 4 OLS Estimation of Effect of Hybrid and Standard Carburetor Performance on EFI *MPG*

	Model 7	Model 8	Model 9	Model 10
$HybridPerf_{t-1}$	0.027 (0.069)			
$StandardPerf_{t-1}$	0.042 (0.185)			
$HybridPerf_{t-2}$		0.243** (0.106)		
$StandardPerf_{t-2}$		−0.192 (0.176)		
$HybridPerf_{t-3}$			0.167** (0.072)	
$StandardPerf_{t-3}$			−0.142 (0.116)	
$HybridPerf_{t-4}$				−0.110 (0.090)
$StandardPerf_{t-4}$				−0.202 (0.321)
Tons	−9.699*** (2.318)	−9.542*** (2.135)	−8.858*** (1.895)	−8.020*** (1.528)
Liters	0.118 (0.451)	0.126 (0.446)	0.130 (0.474)	0.0952 (0.410)
Autotrans	−1.080** (0.342)	−1.077** (0.339)	−1.044** (0.338)	−1.011** (0.329)
Horsepower	−0.0460*** (0.006)	−0.0458*** (0.006)	−0.0473*** (0.007)	−0.0466*** (0.007)
Constant	46.10*** (4.106)	50.33*** (3.264)	48.88*** (2.857)	45.19*** (2.357)
Fixed effects	*ModelYear*, *Carbco* × *CarClass*	*ModelYear*, *Carbco* × *CarClass*	*ModelYear*, *Carbco* × *CarClass*	*ModelYear*, *Carbco* × *CarClass*
Observations	1,379	1,353	1,288	1,203
R-squared	0.598	0.602	0.595	0.614

Notes. The dependent variable is *MPG*. Robust standard errors in parentheses are clustered by carburetor/EFI firm.
*Significant at 10%; **significant at 5%; ***significant at 1%.

performance for any range of lags. These results provide support for Hypothesis 4.

We performed several additional robustness checks. In this paper, we report the results of a continuous measure of patenting activity on hybrid performance; however, we also tested categorical measures of patenting activity levels on performance, which confirmed the results reported here. Furthermore, although there may be variation between firms in business model choices, dynamic capabilities, or environmental factors such as policy changes, the restrictive model reported in the primary results includes fixed effects for year, firm, and car model that control for such between-firm, -year, or -car model variation issues. Nonetheless, in separate robustness checks, we did test for such issues, beyond using a fixed effect control. To test for the potential effect of firm age on inertia and learning from hybrids, we tested a firm age control, but because all firms in the sample were successful incumbents (35 years of age or older), this control did not change the results. We also tested variation in policy changes and found few significant effects, which disappeared completely when tested in combination with our year fixed effects. Finally, we could not identify every carburetor in every car produced (31%) because some car models employed more than one model (and, therefore, including these models could bias the results), and some models were produced in such small quantities that information was unavailable (no repair manuals to identify the carburetor model). A comparison of *MPG* between these models and the sample tested suggests they are very similar.

Discussion

Within the boundary conditions outlined, our results suggest that intergenerational hybrids can play an important role in organizational adaptation and the progression of a technological discontinuity. In particular, we investigated the types of knowledge that may contribute to a high-performing intergenerational hybrid and found that inventive knowledge in the incumbent technology had no significant effect on capturing spillback benefits but that inventive knowledge in the new technology had a significant positive effect, above a threshold level of investment, on capturing spillback benefits. These results are some of the first pieces of evidence, of which we are aware, of how different knowledge types contribute to intergenerational hybrids as well as demonstrating the possibility for spillback benefits. Further robustness checks in models employing categorical rather than continuous variables to model effects of inventive knowledge on hybrid performance replicated the results in the primary analysis.

We also find evidence that developing high-performing hybrids can help organizations adapt to a future technology generation and that these spillforward benefits yield greater performance in the future technology generation.

These are surprising results when considered in the context of previous research about organizational inertia that qualitatively implies that efforts focused on extant technology impede a firm's ability to adapt to the new generation (Utterback 1996). Our results seem to suggest that, at least in this setting, the learning that occurs during the hybrid stage had a positive and significant impact on performance in the future generation. This finding is supported by the anecdotal observation that in the sample of incumbents manufacturing carburetors, the incumbents who developed the highest-performing hybrids survived for five years or more after the EFI technological discontinuity (about 50% of the population), whereas those incumbents who developed the lowest-performing hybrids failed during or shortly after the EFI discontinuity.[9]

This work makes several potential contributions to the extant literature, including the work on organizational adaptation to technology discontinuities (Adner and Kapoor 2012, Eggers 2012, Henderson and Clark 1990, Tripsas and Gavetti 2000, Tushman and Anderson 1986). Although in hindsight such discontinuities are often perceived as short, punctuated equilibriums, in the moment, technology discontinuities are often lengthy, uncertain periods. Prior work has observed intergenerational hybrids but has largely viewed them as organizational dysfunctions. This work, although constrained to an empirical test in a single industry, suggests that intergenerational hybrids may help organizations effectively span this uncertainty, potentially developing valuable supply-side and demand-side knowledge while avoiding common timing mistakes such as leaping too early, entering too late, or ignoring the threat altogether. We provide initial evidence of such positive learning outcomes in the form of increased spillforward benefits: creating higher-performing hybrids increased the ability of incumbents to develop high-performing technologies in the future generation. The anecdotal observation of higher survival among organizations producing high-performing hybrids provides further evidence in this direction.

Our work also contributes to the work on technology strategy that has begun to explore the forces that shape technological evolution (Agarwal and Bayus 2002, Agarwal and Tripsas 2011). This research has begun to explore more fully the evolution of technology discontinuities, in terms of both the many forces shaping the emergence of new technologies and the significant uncertainty constraining incumbent responses (Ansari and Garud 2009, Kapoor and Furr 2015). This paper contributes a more nuanced view of how organizations manage the long period of uncertainty during a potential discontinuity and how the actions of these organizations may reshape the emergence of the new technology paradigm.

Finally, this work contributes to the emerging view of management theory under uncertainty (Furr et al. 2014). This view takes Knight's (1921) categorical delineation between risk (known variables with known probability distributions) and uncertainty (known variables but unknown probability distributions) as a starting point and explores how strategy differs under conditions of risk versus conditions of Knightian uncertainty and unforeseeable uncertainty (where variables are unknown, as are their probability distributions) (Sommer et al. 2009). This work helps to more fully appreciate the extended uncertainty that organizations face during a threatening technology discontinuity along multiple dimensions, including supply-side, demand-side, and timing uncertainty. Fully appreciating such uncertainty helps us avoid oversimplified prescriptions to "leap to new markets," perhaps rooted in a more risk-based view of management, and instead recognize the value of learning tools to resolve the uncertainty as well as to shape the uncertainty itself. For example, in the potential discontinuity between enterprise computing and cloud computing, an intergenerational hybrid has emerged (hybrid cloud). This hybrid serves to help incumbents span the supply-side uncertainty of what cloud computing will eventually become, span the emerging demand-side uncertainty about what customers want (many enterprises want to adopt some cloud services but are not fully trusting of the cloud or are not ready to abandon legacy systems), and span the timing uncertainty of when a discontinuity will occur. But at the same time, the hybrid helps incumbents shape and define the technology discontinuity itself, in terms of both what that discontinuity will be and when it will occur. Although a single example, it helps to illustrate that more fully appreciating uncertainty provides an opportunity to develop new theoretical perspectives and practical recommendations that more appropriately describe strategy under conditions of uncertainty.

This study has several limitations requiring further theoretical and empirical work. First, our study provides an illustration of intergenerational hybrids in a single industry where a technology discontinuity did occur. Although we can point to analogous examples in other industries, the topic of hybrids deserves study in other industries and in settings where a discontinuity threatens but does not occur. Second, our study occurs in an industry where all firms did produce a hybrid; therefore we cannot empirically observe differences between firms producing and not producing hybrids. Although this paper makes a contribution by examining which hybrids contribute to adaptation to the technology discontinuity, the case where some firms produce hybrids and others do not deserves further attention. Third, future research should explore a broader range of boundary conditions—for example, the broader range of organizational factors that may impact whether firms develop a hybrid (e.g., cognitive, political, capability, and business model constraints).

Furthermore, whether hybrids are temporary or permanent deserves further consideration. For example, some intergenerational hybrids, such as the hybrid carburetor or gas light, come and go; others, such as the digital SLR camera, have enduring value. Whether a hybrid acts as a temporary stepping-stone or an enduring new technology depends on one of several factors. First, if components have nonsubstitutable value, such as the reflective lens of a digital SLR camera, then an intergenerational hybrid will be more likely to endure. Second, if customers have nonsubstitutable preferences, then a hybrid may endure. For example, although not a hybrid, dot matrix printers have endured in some customer segments (e.g., repair shops) that prefer the impact printing of dot matrix over laser jet printing (Adner and Snow 2010a, b). Third, hybrids may endure when they perform a unique, unfulfilled purpose not served by either the prior or later technology generations (e.g., the DSLR camera case).

Further development is also needed to understand the conditions under which intergenerational hybrids can help firms learn about a future technology (stepping-stone) versus extend existing technology for enough time to exit the industry (exit options). The answer could depend on one of several variables. One variable may be where innovation occurs—at the product or system level. In cases where the technology discontinuity replaces a product but leaves the system intact, an intergenerational hybrid could more likely act as a stepping-stone, as was the case in the EFI industry. By contrast, if an innovation replaces a product and the larger ecosystem surrounding the product, an intergenerational hybrid may delay a technology discontinuity, as suggested by prior work (Furr and Snow 2014), but may not be sufficient as a stepping-stone. In the gas lighting example, although borrowing the filament from electric lighting may have improved gas lighting, it did not lead to knowledge at the system level (e.g., high-power generators, low-cost copper wiring, etc.) required to leap to the next generation. Although creating a hybrid may not have helped the gas companies innovate in the larger system, the "last gasp" did buy them sufficient time to profitably exit to the adjacent heating and power industries. Therefore, when a technology discontinuity disrupts the system rather than a product, an intergenerational hybrid may act only to defer the technology discontinuity, providing time for incumbents to adapt by finding alternative productive uses for their resources rather than transitioning to the next generation.

Another variable affecting the value of intergenerational hybrids as stepping-stones in a technology discontinuity may be the timing of the hybrid. Technology discontinuities normally progress through periods of initially high uncertainty when a new technology emerges, followed by an era of ferment and experimentation, then closing with a dominant design and a shift from product to process innovation (Anderson and Tushman 1990, Tushman and Anderson 1986). The evolution of a discontinuity may closely model this pattern or be distorted by institutional factors surrounding the emergence of a technology (Ansari and Garud 2009). In either case, the timing of an intergenerational hybrid relative to the progression of the technology likely affects whether the hybrid acts as a stepping-stone. Intergenerational hybrids developed after a dominant design has been established are likely to provide too little learning too late. For example, Blockbuster developed a hybrid brick-and-mortar–online rental model only after Netflix had already established the dominant design and market dominance in the next generation. At the other extreme, it may be possible that developing an intergenerational hybrid too early may limit the value of the hybrid by incorporation of underdeveloped, inferior components at the very emergence of a technology threat or the decay of learning during a long technology emergence. For example, it appears that early attempts to develop hybrid cars suffered from grossly inferior batteries and delays in technology emergence. Perhaps the optimal learning approach would be to develop intergenerational hybrids not at the time of invention but at the time of threat emergence (i.e., commercialization experiments at market boundaries) or when relevant components or architectures are within reach of reasonable investments. We hope to explore these issues in future research.

Conclusion

Although technology discontinuities represent a crucial event for innovation, organization, and strategy scholars, the microprocesses of technology discontinuities remain remarkably opaque. Recently, research has begun to unpack the uncertainty, interactions, and processes that characterize the waves of creative destruction commonly associated with technology discontinuities (Adner and Kapoor 2012, Adner and Snow 2010b, Henderson 1995, Tushman and Anderson 1986). This paper describes one mechanism—namely, how intergenerational hybrids may act as learning tools by which incumbents can develop supply, demand, and timing knowledge that helps them span the uncertainty of a technology discontinuity. This work suggests that intergenerational hybrids deserve further research as a source of innovation and as an adaptation strategy.

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Endnotes

[1]The impact of an intergenerational hybrid may depend on multiple additional factors such as demand heterogeneity (e.g., does a significant group of consumers accept the hybrid?), discontinuity length (e.g., is the length of the discontinuity favorable to hybrids?), ecosystem coinnovation friction (e.g., is the innovation ecosystem amenable to a hybrid?), and hybrid performance (e.g., how does the performance of the hybrid compare to existing and new technologies?). Since these factors also affect the significance of most innovations, not just intergenerational hybrids, we have left them out of the focal discussion. Nonetheless, we acknowledge the importance of these factors and that they may have special cases that apply to hybrids. For the sake of parsimony, we leave this expanded discussion of boundary conditions to later work.

[2]Note that in this boundary condition, we are focusing on investment in the future technology instantiated in the hybrid, but it is also possible that a firm may overinvest in the hybrid itself, which could create inertia and limit learning.

[3]"Higher-performing" could be defined along multiple dimensions, but the example works best if one defines performance as student attendance (e.g., market share). But it can also work if one defines performance as student satisfaction, learning, etc.

[4]For a thorough technical discussion, see Robert Bosch GmbH (2011).

[5]Note that EFI did not face competition among technical alternatives in the new generation like that observed in some discontinuities, such as flat-panel displays, where plasma, LCD, and rear projection competed to replace CRT.

[6]In 1985, European and Japanese automakers held roughly 5% and 20% of the U.S. auto market.

[7]In this program, excess fuel economy performance (e.g., exceeding the regulated minimum) is a fungible benefit that a manufacturer may transfer within the firm from more fuel-efficient models to less fuel-efficient (and often higher-margin) models in order to avoid serious fines. Also note that EPA testing regimes remain consistent during the study period.

[8]It is not possible with the data available to separate these focal cases from alternative patenting inventor/assignee combinations—for instance, from one in which an independent inventor has been contracted to perform research for General Motors. The inclusion of such patents by independent inventors in the patent measure could bias this as a measure of firm experience with a given future technology because licensed independent inventions are less likely to accumulate as firm experience in the sense intended in this study. However, this bias would work against the hypothesized effects and lead to an underestimate rather than an overestimate of firm inventive experience.

[9]Survivors include Aisan, Motorcraft, Hitachi, Weber, and Rochester.

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