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Source Management Science, v. 67, (1), January 2021, p. 201-219

Version Preprint version

DOI 10.1287/mnsc.2019.3538

Publisher INFORMS

Green Technology Development and Adoption: Competition, Regulation, and Uncertainty – A Global Game Approach

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Management Science, Forthcoming

When a government agency considers tightening a standard on a pollutant, the agency often takes into account the proportion of firms that are able to meet the new standard (what we refer to as the industry's "voluntary adoption level"), because a higher proportion indicates a more feasible standard. We develop a novel model of regulation in which the probability of a stricter standard being enacted increases with an industry's voluntary adoption level. In addition, in our model the benefit of a new green technology is both uncertain and correlated across firms, and firms' decisions exhibit both strategic substitutability (because the marketing benefit of a new green technology decreases as more firms adopt it) and complementarity (because the stricter standard is more likely to be enforced as more firms adopt it). To analyze such strategic interaction among firms' decisions under correlated and uncertain payoffs, we use the global game framework recently developed in economics. Our analysis shows that regulation that considers an industry's voluntary adoption level, compared with regulation that ignores it, can more effectively motivate development of a new green technology. Interestingly, uncertainty in the payoff can, in some situations, help promote development of a new green technology. Finally, we find that more aggressive regulation (a higher probability of enforcing a stricter standard for a given voluntary adoption level) encourages more firms to adopt a green technology once the technology becomes available, but may discourage a firm from developing it in the first place when facing intense competition. Therefore, for an industry with intense competition, a government agency should exercise caution about being too aggressive with regulation, which could potentially stifle innovation.
Key words: Environment, global game, regulation, sustainability, technology

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1 Introduction

When a government agency considers tightening a standard on a pollutant, one of the most important factors is the feasibility of a new standard. For example, the United States Environmental Protection Agency (EPA) stated two ways to demonstrate the feasibility of a new standard in their regulatory impact analysis of their Tier 2 fuel standard:

> "The feasibility of meeting the final standards for low sulfur gasoline can be demonstrated in two distinct ways. The first way is to assess whether there is technology available ... The second way is to determine if refiners are already demonstrating that they can meet a low sulfur gasoline standard similar to that contained in this final rule. Evidence that a large number of refineries having various configurations are already meeting a stringent gasoline sulfur program is a more compelling example of feasibility ..." (EPA 1999)

In fact, EPA has repeatedly cited evidence of firms being able to meet a new standard in support of the enactment of the standard. For example, in their regulatory impact analysis of proposed greenhouse gas (GHG) emission standards, EPA stated the following (EPA 2012): "the vast majority of technology we project as being utilized to meet the GHG standards is commercially available and already being used to a limited extent across the fleet ..." The Tier 3 Gasoline Sulfur Standard is another example of industry capability influencing regulation: When proposing this standard, EPA demonstrated its feasibility by claiming that 40 out of 108 gasoline refineries were already able to meet this standard (EPA 2014a). EPA often communicates its policy that takes into account industry capability in public hearings (e.g., EPA 2014b). Such consideration is not a recent development: In early 1999, BP Amoco announced that it would lower the sulfur level in its gasoline in 40 cities around the world; it is believed that this encouraged EPA to set a tougher standard (Kendall and Grossman 1999), as later that year EPA proposed the Tier 2 Gasoline Standard, which required a 90% reduction of the sulfur level in gasoline by 2004. This pattern of looking at early technology adopters before mandating universal adoption is also common in other parts of the world. For example, in Europe, newer emission control technologies became mandatory only after their feasibility had been demonstrated in practice by early adopters (Faiz et al. 1996).

We call the proportion of firms within an industry that have the capability to meet a proposed stricter standard the industry's "voluntary adoption level;" a higher voluntary adoption level could potentially encourage a government agency to tighten regulation. This relationship between industry capability and potential future regulation can in turn affect individual firms' decisions regarding technology adoption: If a firm expects that more firms will voluntarily adopt a new technology to reduce a pollutant, the firm may also be more likely to adopt this technology because mandated adoption becomes more likely. Moreover, mandated adoption is often more costly than voluntary adoption. For example, after the Tier 3 Gasoline Sulfur Standard became effective, refineries that had not met the standard were required to purchase credits to offset their pollution until they updated their technology to bring them into full compliance with the standard (EPA 2014c). As a result, regulation which considers an industry's voluntary adoption level makes firms' actions *strategic complements*.

Despite the fact that regulation often takes industry capability into account, most prior research assumes that government agencies move to stricter standards with fixed probabilities regardless of industry capability. Two prior papers that do model an agency's probability of enforcing a stricter standard incorporating industry capability consider only one firm's capability in a duopoly (Denicolò 2008) or monopoly market (Fleckinger and Glachant 2011), and do not capture strategic complementarity.[1] In addition, most existing research assumes that the benefits of adopting new green technologies to reduce pollutants are deterministic (e.g., Baker and Shittu 2006, Puller 2006). In practice, the benefit of a new technology is often highly uncertain. We aim to provide insight into how this uncertainty of a new technology's payoff, and the strategic complementarity induced by regulation based on industry capability, jointly affect firms' incentives to develop or adopt a new green technology. To do this, we develop a game theoretic model to study firms' decisions on developing, or adopting, a new green technology when there is a possibility of new regulation.

Often after a firm develops and demonstrates the feasibility of a new green technology, other firms follow the leading firm by adopting one of two processes. In the first process, other firms conduct their own research and develop similar technologies. For example, the world's first mass-produced gas-electric car, the Prius, was introduced by Toyota in 1997. After seeing the huge success of the Prius, nearly all major carmakers engaged in hybrid car research, introducing their own versions of hybrid cars (Berman 2007). Then in 2009, the National Highway Traffic Safety Administration (NHTSA) announced the first update to corporate average fuel economy standards for passenger cars in almost two decades, citing the hybrid car technology as one of the major technologies driving the increase in fuel efficiency (NHTSA 2009). In the second process, a leading firm may license the new technology to other competitors. For example, ExxonMobile developed its SCANfining technology to remove sulfur from gasoline (ExxonMobile 2017), not only using this technology for its own refineries, but also licensing the technology to other refineries to help them meet EPA regulations (EPA 2014c). In our analysis, we primarily focus on the first process, but we later show that similar results hold under the second process.

Our model considers the following factors that may affect a firm's decision to innovate or adopt a green technology: potential benefits from the technology, anticipated costs of developing, adopting and using this technology, other firms' decisions, and regulation. The benefits of a green technology are often the primary incentive for a firm to innovate or adopt it. For example, Steve Percy, the former Chairman and CEO of BP America, Inc., pointed out the following benefits of BP's proactive sustainability move: "an enhanced reputation," "market share gains from attracting customers with concerns about the environment," and "reduced risks from unforeseen liabilities [primarily regulatory fines]" (Percy 2013). These benefits are widely applicable to many industries. For example, thanks to its Prius, Toyota has attracted a large number of customers who are concerned about fuel efficiency and carbon emissions (Toyota 2017). The Prius also saved Toyota

[1] In Denicolò (2008) a high-cost firm does not use the clean technology regardless of the other firm's decision, and in Fleckinger and Glachant (2011) there is no interaction between the monopolist and any other firm; see detailed review in §2.

regulatory costs because its fuel economy already satisfied the NHTSA's new standard (NHTSA 2009). Yet, these benefits are inherently uncertain. For example, Toyota forecasted demand for fuel-efficient cars would be high, and released the first mass-produced hybrid vehicle in 1997. By contrast, even in 2004, GM still claimed that hybrid cars did not make sense, regarding hybrid cars as "an interesting curiosity" (Taylor 2006). But, while firms' forecasts of the uncertain benefits are different, these forecasts are typically correlated, because they share some of their underlying data and information sources. In the Prius example, both GM and Toyota used the same public information about gas prices at that time as the basis of their analyses, and they both agreed that gas prices alone could not justify the price of hybrid cars. But they had divergent beliefs on the future of gas prices and consumers' emission concerns. Another example concerns forecasts of electric vehicle demand. As companies and organizations around the world witnessed the better-than-expected improvement of battery costs in 2016, most of them increased their forecasts of the electric vehicle market size significantly compared to one year before, although these forecasts were still different from each other (Lacey 2017). Outside of the automotive industry, it is also common for firms in other industries to look at the same market and generate divergent estimates of the market. For example, Boeing and Airbus both used the same market index (e.g., 8% annual growth of China air passenger traffic), but they generated very different estimates, which led to different corporate strategies with respect to the market (Kotha and Nolan 2005). Specific to our setting, the uncertainty regarding the benefits of a green technology may arise from different sources: The uncertainty concerning an enhanced reputation and demand gain is primarily due to the market and the new green technology itself, whereas the uncertainty around the reduced risks from regulatory fines stems from the uncertainty surrounding government regulation. Our model distinguishes between these two types of benefits.

Of course a company must weigh the potential benefits of a new technology against its costs. In addition to a fixed cost of developing or adopting it, a firm usually incurs a higher production cost in using the new green technology. For example, when BP Amoco promised to reduce the sulfur level in its gasoline in 1999, they estimated that this reduction would increase production costs by 5 or 6 cents per gallon (Kendall and Grossman 1999).

Finally, other firms' decisions and government regulation play important roles in a firm's decision-making. For example, when Toyota was deciding whether to develop the Prius, they considered the possibility that other firms might catch up and the possibility of future regulation (Taylor 2006, Reinhart et al 2006). On the one hand, as more firms adopt the new technology, the reputation enhancement and demand gain for a particular firm become smaller. For example, Toyota's Prius almost dominated the market when it was introduced, but after other firms introduced their hybrid car models, the market share of the Prius shrank (Alternative Fuels and Advanced Vehicle Data Center 2016). In this case, other firms' adoption decisions can discourage a firm from adopting the new technology; firms' actions exhibit *strategic substitutability*. On the other hand, as more firms adopt the new technology, the probability of the government enforcing a stricter standard can increase, yielding a higher incentive to adopt a new technology so as to avoid a higher cost of later adoption. In this case, firms' actions exhibit *strategic complementarity*.

To analyze firms' adoption decisions in equilibrium, taking into account these complex strategic interactions and the uncertainty around the technology's payoff, other firms' actions, and potential regulation, we utilize the *global game* framework recently developed in economics. The strategic interactions imply that a firm must take into account other firms' actions when deciding its own action. But, because of uncertainty, firms do not know what decisions other firms will make. To capture this we posit that firms may share basic market information, but may still disagree about the payoff of adopting the technology; specifically, we model them as observing noisy private signals about the payoff. These private signals imply that a firm cannot predict other firms' actions exactly; the best it can do is to use its own private signal to form a belief on other firms' signals. But since every firm acts based on its belief of other firms' signals, in order to conjecture on other firms' actions a firm must *also* form a belief on other firms' *beliefs* (about other firms' signals), a belief about other firms' belief about other firms' beliefs, and so on. The global game framework is used to address such higher-order beliefs and solve for equilibria in this setting. Crucially, global games differ from typical Bayesian games in which firms' signals are independently distributed: In such Bayesian games one's own signal does not reveal any information about other firms' signals. Thus higher-order beliefs do not play an important role in those games (see, e.g., Morris and Shin 2003).

Our analysis highlights the importance of taking into account the interplay of industry capability and uncertainty about a new green technology's payoff in a firm's development decision. We find that regulation that considers industry capability, compared with regulation that ignores it, more effectively motivates a firm to develop a new green technology when the first-mover advantage from developing this new technology is small. So, for example, in an industry in which firms can easily catch up with a new technology (thus reducing a firm's first-mover advantage), a government agency may wish to use a regulation scheme that explicitly considers industry capability to encourage innovation. Interestingly, we also find that uncertainty of the adoption payoff can help promote a firm's development of a new green technology, specifically when competition is intense and a lot of adopters are anticipated, or when competition is mild and few adopters are anticipated. In the former case, uncertainty may help soften competition by causing some firms to observe low signals. In the latter case, uncertainty may help increase the chance of regulation, eliminating competitive disadvantage, by causing some firms to observe high signals. Finally, we find that more aggressive regulation (which implies a higher probability of enforcing a stricter standard for a given voluntary adoption level) encourages more firms to adopt a green technology once the technology becomes available, but may discourage a firm from developing it in the first place, when facing intense competition. Therefore, for an industry with intense competition, a government agency should avoid being too aggressive with regulation, as this could potentially stifle innovation.

2 Related Literature

Our work is related to four streams of research that study the impact of government regulation on firms' environmental decisions; environmental economics on firms' voluntary overcompliance; technology adoption under network effects; and global games, respectively.

Research that studies the impact of government regulation on firms' environmental decisions has received significant attention recently. The topics studied include mandatory disclosure (e.g., Kalkanci and Plambeck 2018), allocation of emission responsibilities (e.g., Gopalakrishnan et al. 2016, Sunar and Plambeck 2016), uses of financial incentives to motivate green technology innovation and adoption (e.g., Kök et al. 2018, Cohen et al. 2016), and several others. Our work is closely related to the following two topics in this area: firm's innovation under government regulation and the impact of regulatory uncertainty on firms' environmental decisions. Krass et al. (2013) study the roles of environmental taxes, cost subsidies and consumer rebates in motivating a firm to innovate emission-reducing technologies. Innes and Bial (2002) and Puller (2006) examine how a firm can influence regulation through innovation to increase its rivals' compliance costs. Our paper also studies how regulations affect firms' innovation decisions. However, most prior work in this stream studies existing regulations, whereas our work studies the crucial role of uncertainty in both the enactment of regulation and the benefits of a new technology.

Researchers have also examined how firms' environmental decisions are affected by regulatory uncertainty, such as uncertain emission taxes or costs (e.g., Farzin and Kort 2000, Baker and Shittu 2006, Hoen et al. 2015), uncertain policy updating (Tarui and Polasky 2005), and uncertain emission prices in cap-and-trade systems (Drake et al. 2015). In particular, Baker and Shittu (2006) study a single firm's R&D investments to reduce emission under an uncertain carbon tax, and find that a higher carbon tax may lead to a lower investment in alternative low carbon technologies because of imperfect substitution between alternative and conventional technologies. Like Baker and Shittu (2006), all these papers study technology innovation or investments of a single firm, whereas we study technology innovation and adoption of an industry consisting of many firms to highlight the important role of competition. In addition, most existing papers focus on market-based policy instruments, which use price, subsidies, or other market forces to provide incentives for firms to reduce pollution. We consider mandatory compliance to a fixed regulatory standard, which is a mechanism completely different from market-based policy instruments.

There are a few papers that study the impact of regulatory uncertainty under competition. İşlegen et al. (2016) compare domestic and foreign firms' production decisions; they show that variability in the domestic emission costs encourages domestic production because it may mitigate carbon leakage. The primary driving force in İşlegen et al. (2016) is the difference between domestic climate policies and foreign climate policies. By contrast, we focus on a single region under the same regulation, and we show that uncertainty in the technology's payoff can either encourage or discourage the development of a new green technology. Kraft et al. (2013) investigate a firm's decision to replace potentially hazardous substances, and they show that the threat of possible regulation can effectively motivate firms to develop new technologies for hazardous substances reduction. Similarly, Kraft and Raz (2017) study the replacement decisions of a high-end firm and a low-end firm for potentially hazardous substances under potential government regulation, demonstrating that the high-end firm can proactively replace the substance to gain competitive advantage. Our paper also investigates how uncertainty around government regulation affects firms' environmental decisions. However, these papers assume that firms are policy-takers and the probability of government regulation is fixed; our model incorporates the fact that regulation probability often increases with industry capability, reflected by the proportion of firms that can meet the new regulation. In addition, whereas most prior work focuses on regulatory uncertainty, assuming that the market benefits of adopting new technologies are deterministic, we model the uncertainty of these benefits as well, finding that this uncertainty can actually promote the development of a green technology.

Our work is related to the environmental economics literature on firms' voluntary overcompliance. We refer readers to Lyon and Maxwell (2004) and Millimet et al. (2009) for comprehensive reviews on this literature, while discussing here a subgroup of papers most relevant to ours. Lyon and Maxwell (2003) examine the role of the public voluntary agreement, a market-based environmental policy instrument in which the government offers subsidies to firms that voluntarily adopt a green technology. Heyes (2005) shows that firms may reduce their emission voluntarily to signal high emission reduction costs and get lenient limits when the government might set a different emission limit for each firm in an industry. Different from these papers, we focus on a different type of regulation, often called a command-and-control method, which requires all firms to be compliant with the same standard. As such, our results and underlying driving forces are completely different from these two papers. Arora and Gangopadhyay (1995) examine voluntary overcompliance of duopoly firms under existing regulation, and analyze the role of consumers' valuation on environmental quality. Denicolò (2008) studies a duopoly market in which a firm's technology choice affects the likelihood of tougher regulation, and shows that a firm with a competitive advantage might overcomply to trigger tougher regulation that is not socially optimal. Fleckinger and Glachant (2011) study a market with a monopolist that might reduce the probability of new regulation by abating pollution voluntarily. Langpap (2015) analyzes a case in which a regulator offers regulatory relief if a firm joins a voluntary pollution abatement agreement. By contrast, we study an industry consisting of many firms, in which the probability of new regulation increases with the number of firms that adopt a green technology. We focus on interactions among firms that are induced by this regulation. In addition, in all papers reviewed above, firms face no uncertainty in the payoff of the technology, whereas such uncertainty is a key element in our model and results. This setting requires a completely different analytical approach. In addition to these analytical papers, Anton et al. (2004) provide empirical evidence that a firm's voluntary environmental initiatives (e.g., reducing emission) are often driven by market-based pressure from consumers, other firms' similar voluntary environmental initiatives, and the threat of potential future regulation. These factors are also important driving forces for green technology adoption in our model.[2]

Our work is also related to the literature on technology adoption under network effects in economics and operations management. Network effects arise when a user's utility increases with the number of other users, as is the case for technology standards. There is extensive literature on various issues related to network effects, including compatibility choices for products (e.g., Katz and Shapiro 1986 and references therein), coordination failures (see Farrell and Klemeperer 2007 for a summary of the literature), and price competition (e.g., Argenziano 2008 and references therein). Our consideration of strategic complementarity among firms' decisions in developing or adopting a new technology places us within this framework. However, different from the previous literature, our focus is on the effect of regulatory uncertainty on firms' investment decisions; government regulation is seldom studied in this literature.

The notion of global games was originally defined by Carlsson and van Damme (1993); they refer to global games as games of incomplete information in which players receive noisy private signals

[2]Welch et al. (2000) analyze fifty big electric utility firms and find that firms' voluntary initiatives alone are ineffective in reducing emission. Carrión-Flores et al. (2013) empirically show that firms' voluntary pollution reduction initiatives have a negative impact on firms' long-run environmental innovation. These two papers show that regulation after firms' voluntary environmental initiatives is important for promoting pollution reduction.

about a fundamental of the real world, and decide their actions based on their correlated signals. They solve a two-player global game in which players' actions are strategic complements, showing that uncertainty about the payoffs leads to a unique equilibrium because of players' consideration of higher-order beliefs. Morris and Shin (1998, 2005) extend global games to the case of a continuum of players, and to the case in which players' actions are strategic substitutes. Karp et al. (2007) analyze a problem in which players' actions are strategic complements in one region, and strategic substitutes in another region. Building on this theory, global games have been applied to various problems of decentralized coordination among players, including financial crises (Angeletos and Werning 2006), accounting standards comparisons (Plantin et al. 2008), and network analysis (Argenziano 2008). In operations management, Chen and Tang (2015) apply the related concept of higher-order beliefs to study the economic value of private and public information in farmers' production process. To the best of our knowledge our paper is among the first papers to apply the theory of global games to sustainable operations. The use of the global game framework enables us to analyze firms' decisions when strategic complementarity and substitutability are co-present, due to government regulation and firms' competition, respectively.

3 Model

We consider a game of incomplete information between a leading firm and multiple other following firms. We assume a continuum of firms indexed by the interval $[0, 1]$. This assumption is common in the literature on global games; it is reasonable in our context in which a government agency's decision is based on consideration of an entire industry consisting of many firms. For example, there were about 40 car brands in the U.S. in 2008 (Marks 2008), and EPA considered 108 gasoline refineries when proposing the Tier 3 Gasoline Sulfur Standard (EPA 2014a).

The game proceeds as follows: In period 1, a leading firm decides whether to develop a new green technology, which enables the firm to reduce a certain pollutant in its product. If the technology is not developed, the game ends.[3] If it is developed, the game proceeds to period 2 in which other firms decide whether to adopt this technology.[4] In period 3, a government agency announces whether to enforce a stricter standard on the pollutant. The enforcement of the stricter standard occurs with a probability which increases with the proportion of firms that have installed this technology, i.e., the industry's voluntary adoption level. If the new regulation is enforced, those firms that have installed the technology can meet the stricter standard immediately, while the rest of the firms

[3] In §6.2 we discuss an alternative scenario in which the game does not end even if firm 1 does not develop a new green technology.

[4] In our base model in §3, other firms adopt the new green technology originally developed by the leading firm by conducting their own research and developing similar technologies. In §6.1, other firms may adopt the new green technology by licensing it from the leading firm.

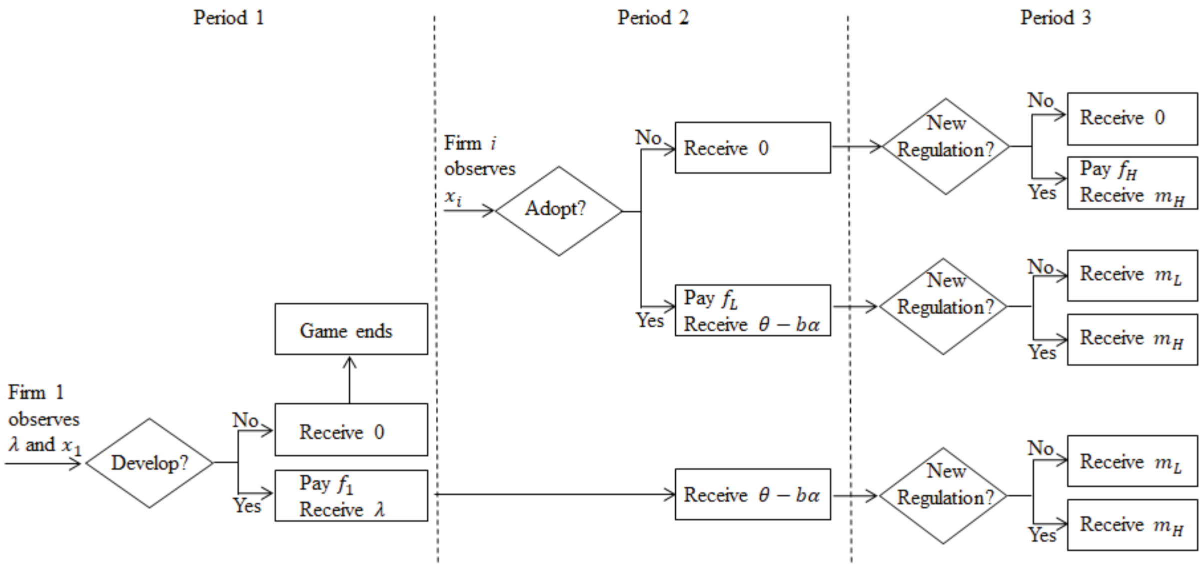

Figure 1: Sequence of Decisions and Events

have to incur extra cost to adopt the technology. The sequence of events is illustrated in Figure 1.

We next present the details of our model in each period: In period 1 the leading firm, denoted as firm 1, has an opportunity to develop a new green technology. Let a_1 denote firm 1's action: $a_1 = 1$ if firm 1 chooses to develop the new technology, or $a_1 = 0$ otherwise. If the firm chooses to develop the new technology, then it incurs a fixed cost f_1 (> 0). We assume that firm 1 implements the technology once it has developed it.[5] After firm 1 develops the technology, it enjoys the first-mover advantage over other firms. The existence of such a first-mover advantage is evident in the example of BP mentioned in §1 (Percy 2013): "BP believed that if it were to move proactively on the topic, it would be much more valuable to be the first rather than second, especially in terms of the reputational benefits." Let λ (≥ 0) denote the signal about the expected payoff of the first-mover advantage. If firm 1 decides not to develop the new technology (i.e., $a_1 = 0$), the game ends.

Prior to making its development decision, in addition to the signal λ about the first-mover advantage, the leading firm privately observes another signal about the benefit that could be affected by competition should other firms adopt the technology in period 2. We assume this benefit is given as $\theta - b\alpha$, where the known parameter b (≥ 0) captures the competition intensity and α ($\in [0, 1]$) represents the proportion of firms that adopt this technology in period 2, i.e., the voluntary adoption level. The unknown parameter θ, representing the maximum of this benefit when $\alpha = 0$, is called the "fundamental" of the new technology. Firm 1 cannot observe θ directly, but instead it observes a noisy private signal $x_1 = \theta + \tilde{\varepsilon}_1$, where $\tilde{\varepsilon}_1$ is distributed uniformly on $[-\epsilon, \epsilon]$ with $\epsilon > 0$ (where ϵ

[5]In §6.2 we discuss a case in which the leading firm may not implement the technology after its development.

is common knowledge).[6] We assume that firm 1's prior belief on θ is very noisy, causing firm 1 to rely fully on its signal x_1 to estimate θ. Such a prior is often called an "improper prior." Note that x_1 as well as θ can be negative, meaning that the technology can reduce firm 1's profit.

In period 2, if firm 1 has developed the technology in period 1 (i.e., $a_1 = 1$), each firm i ($\in [0,1)$) decides whether to adopt the new green technology ($a_i = 1$) or not ($a_i = 0$). If $a_i = 0$, then firm i ($\in [0,1)$) receives zero payoff during this period. If $a_i = 1$, then firm i ($\in [0,1)$) incurs a cost f_L (> 0), while receiving the payoff of $\theta - b\alpha$. Like firm 1, firm i ($\in [0,1)$) observes a noisy private signal $x_i = \theta + \widetilde{\varepsilon}_i$, where $\widetilde{\varepsilon}_i$ is uniformly distributed on $[-\epsilon, \epsilon]$ with $\epsilon > 0$. All $\widetilde{\varepsilon}_i$ are mutually independent as well as independent of $\widetilde{\varepsilon}_1$. The noisy signal $x_i = \theta + \widetilde{\varepsilon}_i$ represents a firm's inaccurate estimate of the new technology's benefits. As illustrated in the examples of hybrid cars and electric cars in §1, the payoff of a new technology is often highly uncertain and firms typically have different but correlated estimates of the payoff. We use $\widetilde{\varepsilon}_i$ to model the noise of firm i's estimate, and use the common fundamental of the technology θ to model the correlation among firms' different signals.[7]

In period 3, a government agency enforces a stricter standard on the pollutant with a probability $q + (1-q)\,\alpha^r$, where $\alpha \in [0,1]$ is the voluntary adoption level, r is a positive constant, and q ($\in [0,1)$) represents the probability the government agency will enforce a stricter standard even when the new green technology has not been adopted by any following firm. We refer to $q + (1-q)\,\alpha^r$ as the "regulation probability." Since $\alpha \le 1$, the larger r is, the less likely the new standard is to be enforced; we refer to settings with larger r values as "less aggressive." Firms' payoffs differ depending on whether or not the new regulation is enforced and whether or not they have adopted the technology.

First, we consider the period-3 payoffs of the firms who have not adopted the new green technology. If the new regulation is not enforced, we normalize their payoffs to zero. If the new regulation is enforced, these firms must adopt the new green technology at a cost f_H (including regulatory fines) in order to meet the stricter standard. The cost of this later adoption is no less than that in period 2 (i.e., $f_H \ge f_L$). For example, after the Tier 3 Gasoline Sulfur Standard became effective, the refineries that could not meet the new standard were subject to up to $25,000 in fines for every day in which they violated the rule (EPA 2014c).[8] Once these firms install the new technology,

[6] We do not assume any specific relationship between λ and x_1. Since these two signals are observed simultaneously before the development decision, their relationship does not provide additional information to the leading firm, and thus does not affect the firm's decision.

[7] We focus on uncertainty in the value of the new technology as well as uncertainty in regulation, while abstracting away from uncertainty in various other dimensions such as lead time and development cost. Our model could be extended to include these, but its analysis would be much more complicated.

[8] We assume $f_H \ge f_L$ to have $(f_H - f_L)$ represent the potential fine under the new regulation. Relaxing this constraint will not change our qualitative insights. We use the probability function $q + (1-q)\,\alpha^r$ to reflect the observed fact that the regulation probability is increasing with the voluntary adoption level. This property can also

they will receive a payoff m_H (≤ 0). The non-positive payoff m_H is used to model the fact that it is typically more costly to use a cleaner green technology and reduce the pollutant than to use a conventional technology (of which the payoff is normalized to zero; see above). Thus, $(-m_H)$ captures the cost of the new regulation to these firms.

Next, we consider the period-3 payoffs of the firms who have already installed the new technology, including both firm 1 and any firm $i \in [0, 1)$ who have adopted the new technology in period 2. We assume these firms receive m_H when the new regulation is enforced, and m_L (≤ 0) when it is not. Under the new regulation, all firms must install the green technology and they receive the same payoff m_H. When the new regulation is not enforced, those firms who have adopted the new technology receive lower payoffs (i.e., $m_L \leq m_H$) because a firm who has installed the green technology has a cost disadvantage over its competitors who have not installed the green technology. Such a cost disadvantage does not exist when the new regulation is enforced, because then all firms must install the green technology. Thus, $(m_H - m_L)$ captures the benefit of the new regulation to a voluntary adopter that eliminates its cost disadvantage.[9]

Taken together, our model captures the two types of benefits from voluntarily adopting a green technology discussed in §1. First, the market benefits through enhanced reputation and demand gain are modeled as the first-mover advantage, denoted by λ, that is exclusive to the leading firm, and the subsequent payoff, $\theta - b\alpha$, that can be received by every voluntary adopter including the leading firm. Second, the reduced regulatory risk is captured by the cost parameters m_H and m_L.

For any given θ and α, if firm i ($\in [0, 1)$) adopts the new green technology in period 2 (i.e., $a_i = 1$ in period 2), then its total expected payoff is $\pi_i(1; \theta, \alpha) \equiv -f_L + \theta - b\alpha + \{q + (1-q)\alpha^r\} m_H + \{1 - q - (1-q)\alpha^r\} m_L$; and if firm i chooses $a_i = 0$, its total expected payoff is $\pi_i(0; \theta, \alpha) \equiv \{q + (1-q)\alpha^r\}(m_H - f_H)$. Thus, the expected gain from adopting the technology, $u_i(\theta, \alpha)$, is

$$u_i(\theta, \alpha) \equiv \pi_i(1; \theta, \alpha) - \pi_i(0; \theta, \alpha) = \theta - b\alpha + \alpha^r (1-q)(f_H - m_L) - (1-q)(f_H - m_L) + f_H - f_L. \quad (1)$$

Since firm i can use its private signal x_i to estimate θ and α, we can also write $u_i(\theta, \alpha)$ as a function of x_i, $u_i(x_i)$. Firm i will adopt the technology (i.e., $a_i = 1$) if and only if $u_i(x_i) \geq 0$.

Similarly, we can derive firm 1's total expected payoff $\pi_1(a_1; \theta, \alpha)$, and then write $u_1(\theta, \alpha)$:

$$u_1(\theta, \alpha) \equiv \pi_1(1; \theta, \alpha) - \pi_1(0; \theta, \alpha) = \lambda - f_1 + m_L + \theta - b\alpha + \{q + \alpha^r(1-q)\}(m_H - m_L). \quad (2)$$

Firm 1 will develop the new green technology in period 1 if and only if $u_1(x_1) \geq 0$. Table 1 summarizes our notation.

be derived if the government agency maximizes social welfare. See §6.2 for the discussion.

[9] In periods 1 and 2, the potential cost disadvantage of a firm who has installed the green technology can be captured in λ and θ, respectively. In §6.2 we discuss another benefit: compliance credits accumulated by voluntary adopters if the new regulation is enforced.

Table 1 Summary of Notation

Symbol	Definition
a_i ($\in \{0,1\}$)	Firm i's action
π_i	Firm i's total expected payoff
u_i	Firm i's gain from developing or adopting the new technology
λ (≥ 0)	Firm 1's expected payoff from the first-mover advantage
θ ($\in \mathbb{R}$)	Fundamental of the new technology
b (≥ 0)	Competition intensity
α ($\in [0,1]$)	Voluntary adoption level
r (> 0)	Regulation probability parameter
q ($\in [0,1]$)	Probability that a stricter standard will be enforced when no following firm adopts the new green technology
$q + (1-q)\alpha^r$	Probability that a stricter standard will be enforced (i.e., regulation probability)
x_i	Firm i's private signal about θ
$\widetilde{\varepsilon}_i$	Noise term in x_i which is uniformly distributed on $[-\epsilon, \epsilon]$
f_1 (> 0)	Firm 1's cost for developing the new technology in period 1
f_L (> 0)	Cost of firm $i\,(\neq 1)$ for adopting the new technology in period 2
f_H ($\geq f_L$)	Cost of firm $i\,(\neq 1)$ for adopting the new technology in period 3
m_L (≤ 0)	Period-3 payoffs of firms who have installed the new technology in period 2, if the stricter standard is not enforced
m_H (≤ 0)	Period-3 payoffs of all firms, if the stricter standard is enforced ($m_L \leq m_H$)

4 Equilibrium Analysis

In this section we analyze firms' decisions in equilibrium. We derive a perfect Bayesian equilibrium as follows. In §4.1, assuming that the new green technology has been developed, we first analyze the decision of firm i ($\in [0,1)$) regarding the adoption of the new green technology in period 2. In §4.2, we then analyze the decision of firm 1 regarding whether to develop the new green technology in period 1. For convenience, we use superscripts (1) and (2) to denote periods 1 and 2.

4.1 Period 2: Adoption of the New Green Technology

We first introduce the global game framework, and then characterize the equilibrium in this period.

4.1.1 Introduction to Global Games

We will use our model as an example to introduce global games. We study a Bayesian Nash equilibrium, which is the standard equilibrium concept in a game of incomplete information. The central tenet in Bayesian Nash equilibria is that players optimize their actions according to their beliefs about others' types and actions. Incomplete information in our model arises from firms' imperfect market research, which generates noisy private signals about the fundamental θ.

Two additional key elements of a global game are *strategic uncertainty* and *higher-order beliefs.* Private noisy signals make firms uncertain about both the fundamental θ and other firms' actions in equilibrium. Such uncertainty about other firms' actions in equilibrium is referred to as *strategic* *uncertainty* in the literature. Strategic uncertainty is important in our setting because of the complementarity caused by the regulation scheme: A firm wants to adopt the technology if all other firms are going to adopt the technology, as then it is very likely to be mandated. Specifically, as more firms adopt the technology (i.e., voluntary adoption level α increases), the new regulation is more likely to be enforced, and firms that have adopted the technology will earn a higher payoff in period 3 under the new regulation than in the case without the new regulation (i.e., $m_H \geq m_L$). In addition, later adoption may be more costly (i.e., $f_H \geq f_L$). For firm $i \in [0, 1)$, $f_H - m_L$ captures the magnitude of complementarity in equation (1); this is the coefficient of $(1-q)\,\alpha^r$.[10]

In a coordination problem with strong complementarity as in our problem, even if the fundamental is sound and everyone has very accurate information, strategic uncertainty may still prevent players from making investment decisions because of *higher-order beliefs*: Players do not know if other players know the sound fundamental, and they do not know if other players know they know the sound fundamental, and so on. Specifically in our model, if firm i receives a signal x_i, it knows that the true value of θ lies between $x_i - \epsilon$ and $x_i + \epsilon$, and it also knows that another firm's signal, a noisy representation of θ, must lie between $x_i - 2\epsilon$ and $x_i + 2\epsilon$. In addition, a firm also forms a belief that other firms know its belief about other firms' signal ranges, and other firms know it has such a belief, and so on.

Morris and Shin (2003) state that higher-order beliefs represent a "natural mathematical way" of studying strategic uncertainty in such coordination games. However, higher-order beliefs in a global game do not impose very high demands on the capacity of the players. In fact, in most cases of binary actions, there exists a simple solution method that can yield the same equilibrium strategies as those obtained from reasoning of higher-order beliefs. In this simple solution method, in order to determine the threshold at which a player is indifferent between two actions, one can think in the following way: The player holds "agnostic" beliefs about others' actions, and the player thinks that the proportion of other players choosing one action over the other is equally likely for any value between 0 and 1; i.e., the proportion is uniformly distributed on the unit interval $[0, 1]$. In this way, one can treat strategic uncertainty as a uniform "random variable" and significantly simplify the analysis. With this simple solution method, the global game setting is rich enough to capture the important role of higher-order beliefs, yet simple enough to be analytically tractable.

Finally, our model features both *strategic complementarity* and *strategic substitutability*. Games

[10] Note that $(1-q)\,\alpha^r$ is the probability of the new regulation, and its coefficient in (1) models the difference between the payoffs of adopting ($a_i = 1$) and not adopting ($a_i = 0$) caused by the new regulation. If the new regulation happens, those that have adopted the technology receive an additional benefit of $(m_H - m_L)$ compared to the case under no new regulation, and those that have not adopted the technology pay f_H and receive m_H. So the coefficient of $(1-q)\,\alpha^r$ is $(m_H - m_L) - (m_H - f_H) = f_H - m_L$.

with strategic complementarity are famous for multiple equilibria under complete information. For example, in our model, if we let $\epsilon = 0$ and $b = 0$, we obtain a game with complete information and strategic complementarity (and without strategic substitutability which we discuss below). In this game, all firms adopting the technology and no firms adopting the technology can both be equilibria. Carlsson and van Damme (1993) and Morris and Shin (1998) show that multiple equilibria are caused by the assumption of complete information under which players can perfectly coordinate with each other. However, with uncertainty, there exists strategic uncertainty that prevents players from knowing others' exact strategies and coordinating perfectly. Using the global game framework, Carlsson and van Damme (1993) and Morris and Shin (1998) analyze such strategic uncertainty and show that only one equilibrium remains under the reasoning of higher-order beliefs. Specifically, strategic uncertainty causes some strategies to become strictly dominated because it pushes players to believe that these strategies are not likely to be played by others.

Strategic substitutability is also a feature of our setting because as more firms adopt the technology, reputation enhancement and demand gain from the green technology will be reduced. This is captured in our model through a firm's benefits from voluntary adoption, $\theta - b\alpha$, which decreases with α. Substitutability can be problematic in that it may result in the nonexistence of an equilibrium, particularly in games of complete information (see, e.g., Vives 2000). For example, in our model, if we let $\epsilon = 0$ and $f_H = m_L = 0$, we obtain a game with complete information and strategic substitutability but without strategic complementarity. We can show that in this case there may not exist a pure-strategy Nash equilibrium: When a firm expects that all other firms would adopt the technology, the firm may be better off not to adopt it because of the substitutability effect. Likewise, when a firm expects that no other firms would adopt the technology, the firm may be better off to adopt it.

When strategic complementarity and substitutability exist simultaneously in a global game, both Morris and Shin (2005) and Karp et al. (2007) show that there exists an equilibrium only if uncertainty is sufficiently large. In the next subsection we will show that this property is preserved in our game, and that this condition can also be expressed in terms of substitutability.

4.1.2 The Equilibrium in Period 2

We now present firms' adoption decisions in equilibrium, and discuss the factors that affect their decisions. Proofs are presented in Online Appendix.

Lemma 1 *There exists a threshold $b^{(2)}$ ($> 2\epsilon$) such that if the competition intensity $b \leq b^{(2)}$, there exists a pure-strategy equilibrium. The threshold $b^{(2)}$ is increasing with ϵ and $f_H - m_L$. In this equilibrium, firm i ($\in [0, 1)$) adopts the green technology if and only if $x_i \geq x^{(2)}$, where*

$x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}\left(1-q\right)\left(f_H - m_L\right)$.

Lemma 1 provides a sufficient condition for the existence of a pure-strategy equilibrium: The competition intensity is not too great. Nonexistence of an equilibrium in games with substitutability is quite common. Morris and Shin (2005) and Karp et al. (2007) show that in global games with substitutability, the substitutability effect needs to be moderate for the existence of a pure-strategy equilibrium. Here the condition $b \leq b^{(2)}$ captures this substitutability effect because we use competition intensity as the parameter for strategic substitutability in the expression $\theta - b\alpha$. The threshold $b^{(2)}$ is increasing with ϵ because firm i's belief regarding the impact of the substitutability effect decreases with ϵ: When the level of uncertainty captured by ϵ becomes larger, firm i's signal becomes a noisier indicator of other firms' signals. As a result, firm i's belief of other firms' decisions changes less as firm i's signal changes, and hence it has a smaller impact on firm i's decision, reducing the certainty of substitutability. Moreover, the substitutability effect can be mitigated by the complementarity effect, which increases with $f_H - m_L$ (see §4.1.1). Hence the threshold $b^{(2)}$ is increasing with $f_H - m_L$ as well.

This condition on b is not restrictive. For moderate r, this condition holds when $b < (1-q) \cdot (f_H - m_L)$. The condition that $b < (1-q)(f_H - m_L)$ corresponds to the effect of government regulation being sufficiently strong such that if all other firms adopt the technology, firm i is encouraged to adopt the technology. To see this, recall that the impact of the voluntary adoption level is captured in (1) as $-b\alpha + \alpha^r (1-q)(f_H - m_L)$, which is positive for $\alpha = 1$ (i.e., all other firms adopt the technology) under the condition $b < (1-q)(f_H - m_L)$. This scenario is what we are interested in.[11] In the rest of the paper, we assume the condition in Lemma 1 is satisfied such that there exists a pure-strategy equilibrium.

When a pure-strategy equilibrium exists, Lemma 1 shows that a firm will adopt the technology if and only if its privately observed signal about the technology's fundamental is sufficiently large (i.e., $x_i \geq x^{(2)}$). Such a strategy is referred to as a "switching" strategy around $x^{(2)}$ in the literature. We can apply the simple solution method in Morris and Shin (2003) to calculate the threshold: At the threshold, firm i is indifferent between adopting and not adopting the technology. Thus it views α as uniformly distributed on $[0,1]$. By solving $\int_0^1 u_i(x_i, \alpha)\, d\alpha = 0$ using (1), we can get the expression of $x^{(2)}$. We provide a formal proof in Online Appendix, as well as more formal description of how to find $x^{(2)}$ using the higher-order belief argument in Lemma O1.[12]

[11] If $b > (1-q)(f_H - m_L)$, then a firm's adoption decision is discouraged when all other firms adopt the technology. In this case, the impact of government regulation is quite weak and it does not play an important role in firms' decision making. See Online Appendix B for further discussion about the existence of an equilibrium.

[12] Higher-order beliefs can be used to derive the equilibrium as follows. First, firm i considers its own signal and gets a strategy as follows: do not adopt if $x_i < \underline{x}^{(0)}$ and adopt if $x_i \geq \overline{x}^{(0)}$, where $\underline{x}^{(0)}$ is sufficiently small such that

Looking now at $x^{(2)}$, we observe that $x^{(2)}$ increases with b, f_L, and r, and that it decreases with m_L and f_H. These are intuitive – firms are more likely to adopt the green technology (i.e., $x^{(2)}$ is lower) when: (i) competition among firms is less intense (i.e., smaller b); (ii) the fixed cost of adopting the technology in period 2 is lower (i.e., lower f_L); (iii) the likelihood of the new regulation being enforced in period 3 is higher because of aggressive regulation (i.e., smaller r); (iv) the competitive disadvantage in period 3 from the costly green technology is lower (i.e., higher m_L); and (v) the penalty due to late adoption in period 3 is larger (i.e., higher f_H).

4.2 Period 1: Development of the New Green Technology

In this section we analyze the leading firm 1's decision regarding whether to develop the new green technology. We characterize firm 1's decision as a function of its private signal x_1 about the technology's fundamental θ. A higher signal x_1 indicates a higher fundamental θ in expectation, which increases the maximum payoff. In addition, a higher signal x_1 affects the substitutability effect and the complementarity effect: With a higher fundamental θ, other firms' signals x_i for $i \in [0, 1)$ are more likely to be higher as well. This implies from Lemma 1 that more firms can be expected to adopt the technology in period 2 (i.e., the voluntary adoption level α will increase), decreasing the payoff $\theta - b\alpha$. This substitutability effect creates a negative incentive for firm 1 to develop the new green technology. However, a higher voluntary adoption level α also creates a positive incentive for firm 1 due to the complementarity effect: With a higher α it is more likely that the new regulation will be enforced in period 3, earning firm 1 a higher payoff m_H, rather than m_L without the new regulation. In equation (2), the complementarity effect on firm 1 is captured by $(m_H - m_L)(1 - q)\alpha^r$.

In order to characterize these two effects on firm 1's decision, we first examine the case in which only the substitutability effect is present in Section 4.2.1. This effect can be isolated by setting $m_H = m_L$. Next, we study the case in which only the complementarity effect exists in Section 4.2.2, by setting $b = 0$. Lastly, by combining both effects, we examine the aggregate effect on firm 1's decision in Section 4.2.3.

firm i does not adopt the technology for $x_i < \underline{x}^{(0)}$ regardless of other firms' decisions, and $\overline{x}^{(0)}$ is sufficiently large such that firm i adopts the technology for $x_i \geq \overline{x}^{(0)}$ regardless of other firms' decisions. Then by considering its belief that all other firms follow a similar strategy with thresholds $\underline{x}^{(0)}$ and $\overline{x}^{(0)}$, firm i refines its strategy and gets a similar strategy with thresholds $\underline{x}^{(1)}$ $(\geq \underline{x}^{(0)})$ and $\overline{x}^{(1)}$ $(\leq \overline{x}^{(0)})$. Next by considering its belief about other firms' strategies with $\underline{x}^{(1)}$ and $\overline{x}^{(1)}$, firm i gets a strategy with thresholds $\underline{x}^{(2)}$ $(\geq \underline{x}^{(1)})$ and $\overline{x}^{(2)}$ $(\leq \overline{x}^{(1)})$. As n approaches ∞, both $\underline{x}^{(n)}$ and $\overline{x}^{(n)}$ approach $x^{(2)}$. See Lemma O1 in Online Appendix A for details.

4.2.1 The Substitutability Effect

We first consider the case in which only the substitutability effect exists for firm 1 by setting $m_H = m_L$.[13] As we discussed earlier, a higher signal x_1 has two effects on firm 1's payoff: a higher expected θ and a higher α. Since $E[\theta] = x_1$, $E[\theta]$ increases linearly with x_1.

However, the marginal effect of a higher x_1 on α varies significantly for different values of x_1. Lemma 1 shows that any other firm i ($\in [0,1)$) will adopt the technology when it observes a signal x_i ($= \theta + \widetilde{\varepsilon}_i$) greater than $x^{(2)}$. Since firm 1's signal is $x_1 = \theta + \widetilde{\varepsilon}_1$, where $\widetilde{\varepsilon}_1$ is uniformly distributed on $[-\epsilon, \epsilon]$, the posterior distribution of the fundamental θ is uniformly distributed on $[x_1 - \epsilon, x_1 + \epsilon]$ for any given x_1, and the posterior distribution of x_i ($= \theta + \widetilde{\varepsilon}_i$) is a symmetric triangular distribution on $[x_1 - 2\epsilon, x_1 + 2\epsilon]$ (see the proof of Proposition 1 in Online Appendix A). So if $x_1 + 2\epsilon < x^{(2)}$, firm 1 knows that no other firms will observe signals higher than the threshold $x^{(2)}$, i.e., the voluntary adoption level α will be zero, and the marginal effect of a higher x_1 on α is also zero. If $x_1 - 2\epsilon \leq x^{(2)} \leq x_1 + 2\epsilon$, then firm 1 expects that some firms will observe signals higher than $x^{(2)}$ and the voluntary adoption level will be positive. But, since the posterior distribution of x_i is a symmetric triangular distribution on $[x_1 - 2\epsilon, x_1 + 2\epsilon]$, the probability density of x_i is highest around x_1. So if x_1 is far away from $x^{(2)}$, a small increase of x_1 does not affect firm 1's expectation of α much; but if x_1 is close to $x^{(2)}$, the probability that other firms' signals are near $x^{(2)}$ is large, and a small increase of x_1 can result in a large increase of firm 1's expectation of α. Finally, if $x_1 - 2\epsilon > x^{(2)}$, firm 1 knows that the voluntary level α has reached the maximum level 1, so the marginal effect of a higher x_1 on α is zero again.

Now we compare the impact of a higher x_1 on the expected fundamental θ with that on the substitutability effect through α. On the one hand, a higher x_1 results in a higher expected fundamental θ, which increases firm 1's payoff. On the other hand, a higher x_1 increases α and causes a higher substitutability effect, which decreases firm 1's payoff. If the substitutability effect is sufficiently small (i.e., $b \leq 2\epsilon$), it is always dominated by the impact of a higher expected fundamental. As a result, firm 1's payoff increases monotonically with x_1, as illustrated in Figure 2(a). If the substitutability effect is sufficiently large (i.e., $b > 2\epsilon$), the impact of the substitutability effect is larger than that of a higher expected fundamental when x_1 is sufficiently close to $x^{(2)}$, but is smaller when it is sufficiently far away. Therefore, firm 1's payoff first increases with x_1, then decreases with x_1 (when x_1 is close to $x^{(2)}$), and finally increases with x_1 again (as illustrated in Figure 2(b)). *In this case, there are regions in which a larger expected benefit reduces the incentive*

[13] In this case, the complementarity effect might still exist for other firms, causing α to increase. However, because $m_H = m_L$, higher α reduces firm 1's payoff (see (2)). Therefore, only the substitutability effect exists for firm 1 in this case.

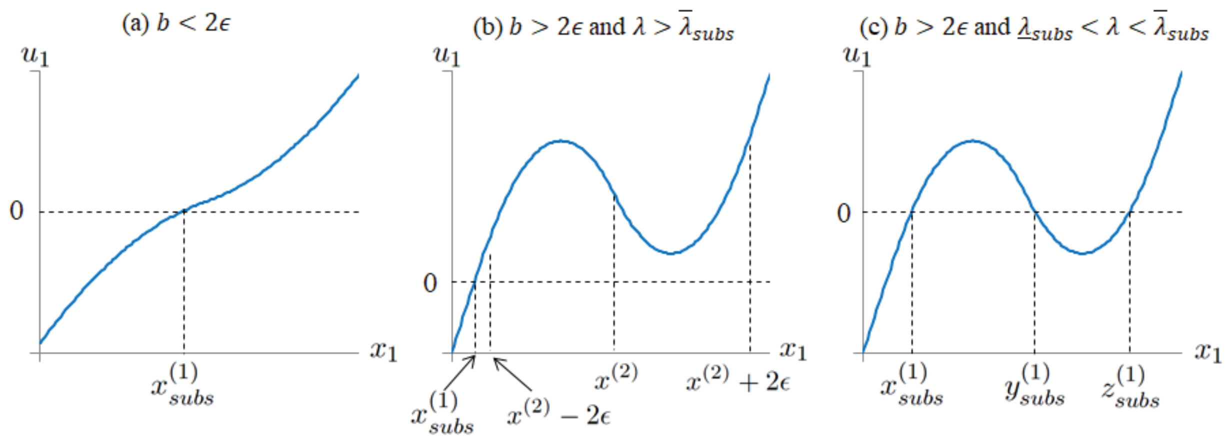

Figure 2: Firm 1's Expected Gain (u_1) from Developing the Technology
Notes. Panel (a), in which competition is not intense ($b < 2\epsilon$), shows that the expected gain (u_1) increases monotonically with firm 1's signal (x_1). Panel (b), in which competition is intense ($b > 2\epsilon$) and the first-mover advantage is large ($\lambda > \overline{\lambda}_{subs}$), shows that the expected gain (u_1) increases nonmonotonically with x_1 and it crosses zero only once. Panel (c), in which competition is intense ($b > 2\epsilon$) and the first-mover advantage is moderate ($\underline{\lambda}_{subs} < \lambda < \overline{\lambda}_{subs}$), shows that the expected gain (u_1) crosses zero three times.

for firm 1 *to develop the technology.* This property of $u_1(x_1)$ leads to the following proposition that characterizes firm 1's equilibrium decision.

Proposition 1 *In the case of $m_H = m_L$, the following results hold in equilibrium:*
(a) If $b \leq 2\epsilon$, then there exists threshold $x^{(1)}_{subs}$ such that firm 1 develops the green technology if and only if $x_1 \geq x^{(1)}_{subs}$. If $b > 2\epsilon$, then there exist real numbers $\underline{\lambda}_{subs}$, $\overline{\lambda}_{subs}$, $x^{(1)}_{subs}$, $y^{(1)}_{subs}$, and $z^{(1)}_{subs}$ (where $\underline{\lambda}_{subs} \leq \overline{\lambda}_{subs}$ and $x^{(1)}_{subs} \leq y^{(1)}_{subs} \leq z^{(1)}_{subs}$) such that: (i) when $\lambda < \underline{\lambda}_{subs}$ or $\lambda > \overline{\lambda}_{subs}$, firm 1 *develops the green technology if and only if $x_1 \geq x^{(1)}_{subs}$; and (ii) when $\underline{\lambda}_{subs} \leq \lambda \leq \overline{\lambda}_{subs}$, firm 1 develops the green technology if and only if $x_1 \in [x^{(1)}_{subs}, y^{(1)}_{subs}] \cup [z^{(1)}_{subs}, \infty)$.*
(b) The thresholds $x^{(1)}_{subs}$ and $z^{(1)}_{subs}$ are nonincreasing with r, and the threshold $y^{(1)}_{subs}$ is nondecreasing with r.
(c) The threshold $x^{(1)}_{subs}$ (resp., $z^{(1)}_{subs}$) is nonincreasing with ϵ if and only if $x^{(1)}_{subs} > x^{(2)}$ (resp., $z^{(1)}_{subs} > x^{(2)}$). The threshold $y^{(1)}_{subs}$ is nondecreasing with ϵ if and only if $y^{(1)}_{subs} > x^{(2)}$.

Proposition 1(a) makes explicit how the magnitude of the substitutability effect affects firm 1's strategy: When the magnitude of the substitutability effect is moderate (i.e., $b \leq 2\epsilon$), the firm's expected gain is increasing with its signal about the fundamental (x_1). Therefore, firm 1 undertakes the development of the new green technology if and only if it observes a sufficiently high signal. This equilibrium strategy takes the same form (a switching strategy) as that of the following firms' adoption decisions (see Lemma 1).

By contrast, when the magnitude of the substitutability effect is large (i.e., $b > 2\epsilon$), firm 1's equilibrium strategy can take two different forms depending on the magnitude of the first-mover advantage (λ), since the expected payoff $u_1(x_1)$ increases with λ. When the first-mover advantage is very large ($\lambda > \overline{\lambda}_{subs}$), firm 1's strategy is again a switching strategy because $u_1(x_1)$ crosses zero only once as illustrated in Figure 2(b). (The intuition for the case when λ is very small is similar and not shown in a figure.) However, when the first-mover advantage is moderate ($\underline{\lambda}_{subs} \leq \lambda \leq \overline{\lambda}_{subs}$), firm 1 develops the technology in equilibrium when it observes a moderate signal between $x^{(1)}_{subs}$ and $y^{(1)}_{subs}$ or a sufficiently high signal above $z^{(1)}_{subs}$. In this case, as illustrated in Figure 2(c), $u_1(x_1)$ crosses zero three times due to the substitutability effect, implying that a higher signal on the technology's fundamental may actually discourage firm 1 from developing the technology.

Proposition 1(b) characterizes the impact of r on firm 1's incentive to develop the new green technology. Recall that the smaller r is, the more likely the new standard is to be enforced for a given voluntary adoption level α. The result that $x^{(1)}_{subs}$ and $z^{(1)}_{subs}$ are nonincreasing in r and $y^{(1)}_{subs}$ is nondecreasing in r implies that a larger chance of a stricter standard being enforced discourages *development* of the new green technology: With a smaller r, the regulation is more aggressive and it encourages more firms to adopt the technology in period 2. As a result, there are more competing firms, and the substitutability effect, which creates a negative incentive for firm 1, becomes more pronounced.

Proposition 1(c) shows that a higher magnitude of uncertainty encourages firm 1's development of the new green technology if and only if the thresholds are larger than $x^{(2)}$. (Notice that smaller $x^{(1)}_{subs}$ or $z^{(1)}_{subs}$ and larger $y^{(1)}_{subs}$ indicate a larger region of x_1 in which firm 1 develops the technology.) Again, since firm 1's posterior distribution of firm i's ($i \neq 1$) signal is a triangular distribution on $[x_1 - 2\epsilon, x_1 + 2\epsilon]$, as ϵ increases, firm 1 expects firm i's signal to be more spread out. If $x_1 > x^{(2)}$, observe from Figure 3 that the probability of $x_i < x^{(2)}$ increases as ϵ increases. As a result, fewer firms will observe signals larger than $x^{(2)}$ and adopt the technology. Since only the substitutability effect exists, fewer adopting firms encourage firm 1 to develop the technology.

4.2.2 The Complementarity Effect

Next we consider the case in which only the complementarity effect exists by setting $b = 0$, while $m_H > m_L$. Following the same procedure as in §4.2.1, we can show that the marginal effect of a higher signal x_1 on the complementarity effect is larger if x_1 is closer to $x^{(2)}$. Furthermore, the complementarity effect as well as a higher fundamental creates positive incentives for firm 1 to develop the technology. As a result, a higher x_1 always increases firm 1's payoff, and hence firm 1's payoff function crosses zero only once. Therefore, in equilibrium, firm 1 chooses a switching strategy around a threshold $x^{(1)}_{comp}$ as stated in Proposition 2(a).

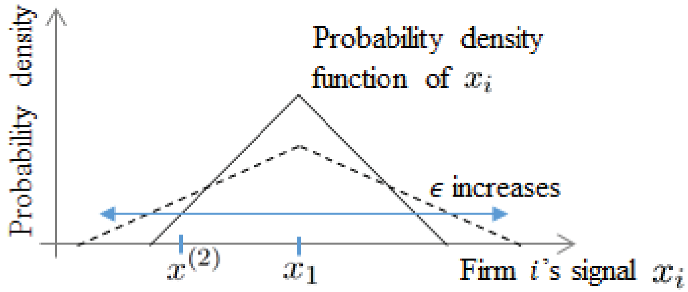

Figure 3: The Impact of the Level of Uncertainty (ϵ) on the Probability Distribution of Firm i's signal (x_i)
Notes. As the level of uncertainty (ϵ) increases, the posterior probability of firm i observing a signal smaller than the threshold $x^{(2)}$ increases.

Proposition 2 *In the case of $b = 0$, the following results hold in equilibrium:*

(a) There exists threshold $x^{(1)}_{comp}$ such that firm 1 develops the green technology if and only if $x_1 \geq x^{(1)}_{comp}$.

(b) The threshold $x^{(1)}_{comp}$ is nondecreasing with r.

(c) The threshold $x^{(1)}_{comp}$ is nonincreasing with ϵ if and only if $x^{(1)}_{comp} < x^{(2)}$.

Proposition 2(b) suggests that the impact of r on the firm's incentive to develop the new green technology is opposite to that in Proposition 1(b): When the complementarity effect exists, a larger chance of the stricter standard being enforced incentivizes firm 1 to develop the new green technology, whereas it discourages firm 1 from doing so in the presence of the substitutability effect. Similarly, Proposition 2(c) suggests that the magnitude of uncertainty ϵ likewise has an effect opposite to the effect shown in Proposition 1(c). In this case, larger uncertainty encourages firm 1 to develop the technology if it observes a relatively low payoff signal ($x^{(1)}_{comp} < x^{(2)}$): The low payoff signal indicates that other firms' signals are likely to be low and there will likely not be a lot of adopters. But larger uncertainty can cause some firms to observe large signals and increase the number of adopters. As a result, the probability of the new regulation is higher with larger uncertainty, benefiting firm 1 in the presence of only the complementarity effect.

4.2.3 The Aggregate Effect

By combining the results stated in Propositions 1 and 2, we derive the following equilibrium for the general case in which both substitutability and complementarity effects are present (i.e., $b \geq 0$ and $m_H \geq m_L$).

Proposition 3 *(a) Proposition 1(a) continues to hold (with thresholds $\underline{\lambda}_{aggr}$, $\overline{\lambda}_{aggr}$, $x^{(1)}_{aggr}$, $y^{(1)}_{aggr}$, and $z^{(1)}_{aggr}$ replacing $\underline{\lambda}_{subs}$, $\overline{\lambda}_{subs}$, $x^{(1)}_{subs}$, $y^{(1)}_{subs}$, and $z^{(1)}_{subs}$, respectively) except that the condition $b \leq 2\epsilon$*

is replaced with $b \leq b^{(1)}$*, where* $2\epsilon \leq b^{(1)} < b^{(2)}$*, and* $b^{(1)}$ *is increasing with* ϵ *and* $m_H - m_L$*.*

(b) There exists b_x^* *such that the threshold* $x_{aggr}^{(1)}$ *is nonincreasing with* r *if and only if* $b > b_x^*$*. The same result applies to* $z_{aggr}^{(1)}$ *with threshold* b_z^**. There exists* b_y^* *such that the threshold* $y_{aggr}^{(1)}$ *is nondecreasing with* r *if and only if* $b > b_y^*$*.*

(c) There exists b_x^{**} *such that the threshold* $x_{aggr}^{(1)}$ *is nonincreasing with* ϵ *if one of the following two conditions is satisfied: (1)* $b > b_x^{**}$ *and* $x_{aggr}^{(1)} > x^{(2)}$*, and (2)* $b < b_x^{**}$ *and* $x_{aggr}^{(1)} < x^{(2)}$*. The same result applies to* $z_{aggr}^{(1)}$ *with threshold* b_z^{**}*. There exists* b_y^{**} *such that the threshold* $y_{aggr}^{(1)}$ *is nondecreasing with* ϵ *if one of the following two conditions is satisfied: (1)* $b > b_y^{**}$ *and* $x_{aggr}^{(1)} > x^{(2)}$*, and (2)* $b < b_y^{**}$ *and* $x_{aggr}^{(1)} < x^{(2)}$*.*

When both complementarity and substitutability are present, a larger signal x_1 affects the expected value of the fundamental, the complementarity effect, and the substitutability effect. When b is sufficiently small (i.e., $b \leq b^{(1)}$), the former two effects dominate the last one, and the expected gain $u_1(x_1)$ increases with the signal x_1. In this case, firm 1's strategy is a switching strategy.

When b is larger (i.e., $b^{(1)} < b \leq b^{(2)}$), the marginal effect of a higher signal on substitutability dominates that of complementarity and the fundamental in some regions. Therefore the negative impact of substitutability can make firm 1's expected gain $u_1(x_1)$ change non-monotonically with x_1. In this case, similar to Proposition 1(a), firm 1 may develop the technology if it observes a signal in two separate regions. However, the threshold $b^{(1)}$ is larger than the threshold 2ϵ in Proposition 1(a) because the negative impact of substitutability is mitigated by the positive impact of complementarity.

Notice that the threshold $b^{(1)}$ in this period is always smaller than the threshold $b^{(2)}$ in the second period. This is caused by the weaker complementarity effect for firm 1 than that for the other firms. First, for $i \in [0,1)$ later adoption is more costly than earlier adoption (i.e., $f_H \geq f_L$) because of potential regulatory fines; but firm 1 is immune to this factor because if it does not develop the technology, there is no technology available for the new regulation. Second, for firm $i \in [0,1)$, the magnitude of complementarity is captured in (1) by $f_H - m_L$ as the coefficient of $(1-q)\alpha^r$ (recall that $f_H > 0$ and $m_H \leq 0$ from §3). For firm 1, the magnitude of complementarity is captured in (2) by $m_H - m_L$ as the coefficient of $(1-q)\alpha^r$. As a result, there always exists an interval $(b^{(1)}, b^{(2)}]$ for b in which the substitutability effect is sufficiently small for the existence of an equilibrium in period 2, and sufficiently large for the non-monotonic gain of firm 1. In addition, the length of this region is increasing with f_H. So the higher the regulatory fines are, the higher chance there is for firm 1 to have a non-monotonic gain.

Proposition 3(b) combines the results of Proposition 1(b) and Proposition 2(b). As discussed earlier, more aggressive regulation that has a greater probability of enforcing the stricter standard for a given voluntary adoption level (i.e., a lower r) discourages firm 1 from developing the new green technology under substitutability, whereas it encourages the firm to do so under complementarity. When both effects are present, Proposition 3(b) shows that when the competition intensity b is sufficiently large, the former substitutability effect outweighs the latter complementarity effect.

Proposition 3(c) combines the results of Proposition 1(c) and Proposition 2(c). A larger magnitude of uncertainty results in fewer adopting firms if and only if $x_1 > x^{(2)}$, as discussed in §4.2.1. Fewer adopting firms creates a positive incentive for firm 1 when the competition intensity b is so large that the substitutability effect outweighs the complementarity effect. In this case, a larger magnitude of uncertainty encourages the development of the green technology if firm 1's thresholds are larger than $x^{(2)}$.[14]

These results depend on the magnitude of b, the competition intensity through the expression $\theta - b\alpha$ that models the benefits of enhanced reputation and demand gains. In the example of hybrid cars, competition is intense: Toyota's Prius received huge demand after it was introduced, but after other firms introduce their hybrid car models, the market share of the Prius shrank (Alternative Fuels and Advanced Vehicle Data Center 2016). On the other hand, according to Percy (2013), when BP was proactively implementing sustainability strategies, including selling low-sulfur gas, the primary benefit was enhanced reputation that helped them build good relationships with the government. Such good relationships may have helped facilitate their later business operations, such as their merger with Amoco. In this case, competition may be moderate because this kind of reputation enhancement is not easily undermined by competition.

Proposition 3 bears an important policy implication. In highly competitive industries, if the government is too aggressive in moving to stricter new regulation (i.e., r is too small), they may discourage innovation (as suggested by Proposition 3(b)). Therefore, the government agency should be cautious against being too aggressive on regulation that may actually stifle innovation. This implication may be consistent with NHTSA's current practice. Although hybrid cars can greatly enhance fuel economy, no stricter new regulation on fuel economy was enforced for many years after hybrid cars became commercially available. Stricter regulation on fuel economy was introduced only in 2009, when most major car manufacturers had already developed their hybrid models (NHTSA 2009).

[14]The result in Proposition 3(b) depends on the threshold b_x^*. In Online Appendix B we compare b_x^* with $b^{(2)}$ in the existence condition of Lemma 1. We show that there always exists an interval of $x_{aggr}^{(1)}$ in which $b_x^* < b^{(2)}$. Therefore, the scenarios $b < b_x^*$ and $b > b_x^*$ in Proposition 3(b) are both valid. Similarly, all scenarios in Proposition 3(c) are also valid.

Proposition 3 also provides managerial insights for firms. When deciding the development of this technology, a firm should treat a relatively high payoff signal carefully: As suggested by Proposition 3(a), this relatively high signal may indicate that other firms will adopt the technology and reduce the benefit of developing the technology. Finally, Proposition 3(c) shows that uncertainty concerning the new technology's benefits can help motivate a firm to develop the new technology. When many adopters are anticipated and competition is intense, uncertainty may help soften competition by causing some firms to underestimate the benefits of the new technology. Similarly, when few adopters are anticipated and competition is moderate, uncertainty may help increase the chance of regulation by causing some firms to observe high signals, in this case motivating development.

5 Comparison to a Benchmark in which Regulation is Independent of a Voluntary Adoption Level

To study the impact of a government's consideration of industry capability on firms' decisions, we compare our model of regulation that considers industry capability with a regulation scheme that ignores it. To model the latter regulation scheme, we assume that the government agency enforces a stricter new standard with a known fixed probability $\widehat{q}$ $(\in (0,1))$, which does not depend on α. All other assumptions remain the same as in the base model. Following a procedure similar to that in §4, we can characterize the equilibrium in this case as follows:

Lemma 2 *Suppose that the regulation probability is $\widehat{q}$. Then there exists a pure-strategy equilibrium if $b \le 2\epsilon$. In equilibrium, the following results hold:*
(a) Firm i $(\in [0,1))$ adopts the green technology in period 2 if and only if $x_i \ge \widehat{x}^{(2)}$, where $\widehat{x}^{(2)} = \frac{1}{2}b + f_L - (1-\widehat{q})\, m_L - \widehat{q} f_H$.
(b) There exists a threshold $\widehat{x}^{(1)}$ such that firm 1 develops the green technology if and only if $x_1 \ge \widehat{x}^{(1)}$.

Lemma 2(a) shows that firms' equilibrium strategies in period 2 take a similar form to those under regulation which considers industry capability, although the value of the threshold is different from that of the corresponding threshold in our base model. Also, in both cases, sufficiently small levels of competition intensity are required for the existence of an equilibrium, because of the impact of strategic substitutability. We know from §4.1.2 that for our base model the impact of substitutability decreases with ϵ, and it can be mitigated by strategic complementarity. But for the fixed probability model, due to the absence of complementarity under regulation ignoring industry capability, the threshold for the competition intensity (2ϵ) is smaller than that under a regulation scheme which considers industry capability $(b^{(2)})$.

Lemma 2(b) shows that firm 1's equilibrium strategy is a switching strategy for the fixed probability model. Recall from part (a) that when $b \leq 2\epsilon$, a pure-strategy equilibrium exists in period 2. In this case, firm 1's expected gain always increases with the signal x_1. The intuition is similar to that of Proposition 3(a) when $b \leq b^{(1)}$.

We next compare a firm's incentive to develop a new green technology under regulation which considers industry capability with that under regulation which ignores industry capability. To this end, we compare the threshold $\widehat{x}^{(1)}$ in Lemma 2 with $x_{aggr}^{(1)}$ in Proposition 3, assuming that both regulation settings are equally good at motivating firms to adopt the new technology in period 2: Because $\widehat{x}^{(2)}$ is a function of $\widehat{q}$ and $x^{(2)}$ is a function of q and r, we choose values of $\widehat{q}$, q and r such that the two thresholds are the same. Given that both regulation schemes are equally effective in period 2, the following proposition establishes a condition under which one is more effective in period 1 than the other.[15]

Proposition 4 *There exists threshold $\widehat{\lambda}$ such that $x_{aggr}^{(1)} \leq \widehat{x}^{(1)}$ if and only if $\lambda \leq \widehat{\lambda}$.*

Proposition 4 shows that when the first-mover advantage λ is small, regulation that considers industry capability is more effective in incentivizing firm 1 to develop the new green technology. This is because when the first-mover advantage λ is small, firm 1 needs larger payoffs in periods 2 and 3 to earn a positive expected gain in total. When firm 1 observes a large signal x_1, other firms are also likely to observe large signals. As a result, the voluntary adoption level α is likely to be high, cutting firm 1's payoff due to competition. But under regulation which considers industry capability, the probability of regulation is also likely to be high, because it increases with the voluntary adoption level. In this case there is a high probability that firm 1's cost disadvantage in period 3 will be eliminated due to mandatory adoption. Therefore, regulation that considers industry capability works better when the first-mover advantage λ is small.

Proposition 4 bears important policy implications. A government agency's consideration of industry capability is more effective in motivating a firm to develop a green technology only when the first-mover advantage is small. The first-mover advantage is likely to be small when other firms can catch up with the technology quickly. For example, as mentioned in §1, BP Amoco announced that it would lower the sulfur level in its gasoline in 40 cities in 1999. A few months later, Koch Petroleum followed BP by announcing that they would also sell gasoline with lower sulfur levels (Koch 1999). In this case our result suggests that regulation based on industry capability might

[15] We did not simply let $\widehat{q} = q$ because $\widehat{q}$ is the total probability of regulation in the independent model; this same quantity is $q + (1 - q)\,\alpha^r$ in the model that considers industry capability. Two parameters, q and $\widehat{q}$, affect firms similarly: In Proposition O1 of Online Appendix A we show that $x_{aggr}^{(1)}$ ($\widehat{x}^{(1)}$) is decreasing with q ($\widehat{q}$) if b is sufficiently small, and $x_{aggr}^{(2)}$ ($\widehat{x}^{(2)}$) is decreasing with q ($\widehat{q}$).

have been advisable.

6 Extensions

In §6.1 we present an extension in which a leading firm can choose whether to license the technology to other firms, and in §6.2 we discuss other extensions and robustness checks.

6.1 Licensing of the Technology

Our base model focuses on the adoption process in which after the leading firm demonstrates the feasibility and features of a new technology, other firms may conduct their own research and develop similar technologies. In this section we study a case in which a leading firm can choose whether to license the technology to other competitors. This case is related to Hattori (2017) who analyzes a monopolist's decisions on innovation level and licensing fees to downstream buyers under existing market-based policy instruments (such as emission taxes and development subsidies). Our setting differs in that we examine a leading firm's development and licensing decisions when there is potential new regulation with endogenous probability, which is a command-and-control instrument. As such, the results and driving forces are very different.

The sequence of events is as follows: In period 1, firm 1 decides whether to develop a new green technology. If firm 1 develops the technology, then at the beginning of period 2, firm 1 decides whether to license the technology, and a licensing price $p^{(2)}$ for this period if it decides to do so. If the technology is available for licensing, firm i has three options in period 2: (option 1) buying the technology from firm 1 at the price $p^{(2)}$, (option 2) developing the technology by itself incurring a cost f_L, and (option 3) not adopting the technology at all; if the technology is not available for licensing firm i only has options 2 and 3. In period 3, with probability $q+(1-q)\,\alpha^r$, the government enforces a new regulation that mandates the technology. After the new regulation is enforced, firm 1 decides whether to license the technology and a licensing price $p^{(3)}$ for this period, if it decides to do so. If the technology is available for licensing, those firms that have not adopted the technology can either buy the technology from firm 1 at the price $p^{(3)}$, or develop the technology by themselves at the cost f_L; if firm 1 chooses not to license, they only have the latter option. In addition, these firms pay a regulatory fine of $f_H - f_L$ (≥ 0).[16]

We next analyze firms' decisions in each period. In period 3, firm i buys the technology if and only if $p^{(3)} \leq f_L$. Denote by c the marginal cost of licensing the technology to one firm. If $c \leq f_L$, firm 1 can set $p^{(3)} = f_L$ to gain the maximum profit $\{q+(1-q)\,\alpha^r\}\,(1-\alpha)\,(f_L - c)$, and if $c > f_L$, firm 1 does not license the technology. In either case, the cost for firm i is f_L. In period 2, following

[16] This additional cost $f_H - f_L$ is introduced to maintain consistency with the base model, in which the adoption cost is f_L in period 2 and f_H in period 3, and $f_H \geq f_L$ because of the possible regulatory fine. Similarly, one can interpret $f_H - f_L$ as the regulatory fine in the base model.

the same procedure as in §3, we obtain firm i's expected gain from buying the technology and its gain from developing the technology by itself, respectively, as follows:

$$\begin{aligned}\widetilde{u}_i(\theta,\alpha,p^{(2)}) &= \theta - b\alpha + \alpha^r(1-q)(f_H - m_L) + (1-q)m_L - p^{(2)} + qf_H,\\ u_i(\theta,\alpha) &= \theta - b\alpha + \alpha^r(1-q)(f_H - m_L) - (1-q)(f_H - m_L) + f_H - f_L,\end{aligned}$$

where $u_i(\theta,\alpha)$ is the same as (1) (in §3). Since $\widetilde{u}_i(\theta,\alpha,p^{(2)}) - u_i(\theta,\alpha) = f_L - p^{(2)}$, as expected, firm i buys the technology in period 2 if $p^{(2)} \leq f_L$ and $E\left[\widetilde{u}_i(\theta,\alpha,p^{(2)})|x_i\right]$, the expected value of $\widetilde{u}_i(\theta,\alpha,p^{(2)})$ given its signal x_i, is positive. So firm 1 will set $p^{(2)} \leq f_L$ if it licenses the technology to other firms. In this case, firm 1's profit from licensing is $\left(p^{(2)} - c\right)\alpha$ in period 2 and $\max\{0, f_L - c\}(1-\alpha)$ in period 3. Thus, we can modify firm 1's expected gain in (2) as

$$\widetilde{u}_1(\theta,\alpha,p^{(2)}) = \lambda - f_1 + m_L + \theta - (b - p^{(2)} + c)\alpha + \{q + (1-q)\alpha^r\}\left[m_H - m_L + (1-\alpha)\max\{0, f_L - c\}\right]. \quad (3)$$

If it does not license the technology in period 2, its expected gain can be expressed as

$$u_1(\theta,\alpha) = \lambda - f_1 + m_L + \theta - b\alpha + \{q + (1-q)\alpha^r\}\left[m_H - m_L + (1-\alpha)\max\{0, f_L - c\}\right].$$

Firm 1 licenses the technology if the following conditions are satisfied: $\max_{p^{(2)} \leq f_L} E\left[\widetilde{u}_1(\theta,\alpha,p^{(2)})|x_1\right] \geq E\left[u_1(\theta,\alpha)|x_1\right]$ and $\max_{p^{(2)} \leq f_L} E\left[\widetilde{u}_1(\theta,\alpha,p^{(2)})|x_1\right] \geq 0$.

To analyze firm 1's decision in period 2, we need to derive an optimal price by solving the maximization problem $\max_{p^{(2)} \leq f_L} E\left[\widetilde{u}_1(\theta,\alpha,p^{(2)})|x_1\right]$. However, note from (3) that $\widetilde{u}_1(\theta,\alpha,p^{(2)})$ is a nonlinear function of α, and α is a function of $p^{(2)}$ and a random variable x_1. Thus, a closed-form expression of the optimal price does not exist, making the analytical comparison between $\max_{p^{(2)} \leq f_L} E\left[\widetilde{u}_1(\theta,\alpha,p^{(2)})|x_1\right]$ and $E\left[u_1(\theta,\alpha)|x_1\right]$ impossible. For this reason, we analyze this problem numerically via a large numerical experiment.[17]

We observe the intuitive result that firm 1 licenses the technology in period 2 if the marginal cost of licensing the technology is sufficiently small. If the marginal cost is high, firm 1 does not have much freedom: If it chooses a high price, other firms may not buy the technology, and if it chooses a low price, it may incur losses from licensing.

The case when firm 1 does not license the technology is similar to the base model. For the case when firm 1 finds it optimal to license the technology, in addition to the effects of substitutability and complementarity, there is another effect from firm 1's sales of the technology. This sales effect can mitigate the substitutability effect and change the threshold values obtained earlier, but it does

[17] We considered $291,600$ scenarios with the following parameter values that cover various possible scenarios: $b \in \{0, 0.5, 1, 2\}$, $\lambda - f_1 \in \{-4, -2, 0, 2, 4\}$, $r \in \{0.3, 0.6, 1, 1.6, 3\}$, $\epsilon \in \{0.3, 1, 2\}$, $m_H \in \{0, -0.5, -2\}$, $m_L \in \{m_H, m_H - 0.5, m_H - 2\}$, $f_L \in \{0.5, 1, 2\}$, $f_H \in \{f_L, f_L + 1, f_L + 2\}$, $q \in \{0, 0.1, 0.2, 0.5\}$, and $c \in \{0.5, 1, 2\}$.

not change the qualitative insights. This is because this sales effect is similar to the complementarity effect: As more firms buy the technology from firm 1, firm 1's payoff increases, so firm 1 is more likely to develop the technology. If the competition intensity b is sufficiently small, the sales and complementarity effects may dominate the substitutability effect, and the insights are similar to the case when the complementarity effect is sufficiently large in the base model. If b is sufficiently large, the substitutability effect may dominate the other two, and the insights are similar to the case when the substitutability effect is sufficiently large in the base model. The latter case is often observed when c is high: With a large c, it is possible that firm 1 is better off licensing the technology, but the sales effect is weak because firm 1 cannot set the price higher than f_L.

So far we have focused on the case in which the technology is developed by a leading firm in the same tier as other adopters. Sometimes a new green technology is developed by a supplier who then licenses it to *downstream* firms. Since the supplier does not compete with downstream firms directly, the substitutability effect caused by competition does not exist. Similarly, there is no complementarity effect caused by regulation. Thus, the supplier decides whether to develop a new green technology simply based on how much profit it can expect to generate. This effect from selling the technology is the same as the sales effect discussed above. Thus, the results in this case are similar to the results in the case when the complementarity effect is sufficiently large in the base model.[18]

6.2 Other Extensions

We have also studied other extensions to demonstrate the robustness of our insights. We briefly summarize these extensions in this section, while referring readers to the Online Appendix for details. We have conducted further analysis on the existence of equilibria and compared different thresholds in Online Appendix B. In the base model, we assume that the game ends if the leading firm does not develop the technology; in Online Appendix C we relax this assumption and analyze an alternative scenario in which even if firm 1 does not develop a new green technology, the game does not end due to the possibility that another firm may discover a similar technology. Online Appendix D considers a case in which the leading firm may not implement the technology after its development. In the base model, a voluntary adopter obtains the benefit of eliminating its cost disadvantage if the new regulation is enforced. In Online Appendix E we examine another benefit: compliance credits accumulated by voluntary adopters if the new regulation is enforced. Online

[18] We can express the supplier's expected profit for any given α as follows: $\widetilde{u}_s(\alpha, p^{(2)}) = -f_1 + (p^{(2)} - c)\alpha + \{q + (1-q)\alpha^r\}(1-\alpha)\max\{0, f_L - c\}$, where the second and third terms capture the sales effect as in $\widetilde{u}_1(\theta, \alpha, p^{(2)})$ in (3). $\widetilde{u}_1(\theta, \alpha, p^{(2)})$ has additional terms, $-b\alpha$ and $\{q + (1-q)\alpha^r\}(m_H - m_L)$, that capture the substitutability and complementarity effects, respectively. As more firms adopt the technology, the sales effect increases in a manner similar to the complementarity effect in the base model.

Appendix F shows that our main insights continue to hold when the government agency maximizes social welfare. Online Appendices G and H examine two additional extensions: The leading firm has an information advantage over other firms, and new regulation might reduce voluntary adopters' payoffs. Our qualitative insights continue to hold in these extensions as well.

To demonstrate the critical role of interactions among firms in period 2, we study an alternative model that uses a single representative firm to represent the industry in Online Appendix I. We find that how regulation affects firms' decisions is very different in this model. In Online Appendix J we examine another alternative model in which firms' payoffs are deterministic and heterogeneous. We show that the equilibrium behaviors are also very different in this alternative model, highlighting the important role of uncertainty.

7 Conclusion

A government agency's potential regulatory action is an important driving force for firms to develop and adopt new green technologies. Existing research assumes that a government agency's action is independent of industry capability, and that the benefit of a new technology is either known or independent of other firms' actions. In practice, however, a government agency often takes into account industry capability, and firms face uncertainty in the technology's benefits and in other firms' actions. In this case firms' decisions exhibit both strategic substitutability (because the marketing benefit of a new green technology decreases as more firms adopt it) and complementarity (because the stricter standard is more likely to be enforced as more firms adopt it). We develop a novel model based on the global game that captures these realistic features, and examines how they affect firms' development and adoption decisions.

Our analysis bears important policy implications. We show that regulation that considers an industry's voluntary adoption level–compared with regulation that ignores it–can more effectively motivate development of a new green technology when the first-mover advantage from the technology is low. Therefore, for an industry in which firms can easily catch up with a new technology (thus reducing a firm's first-mover advantage), regulation that considers industry capability should be considered to encourage innovation. In addition, when such regulation is used, our findings show how more aggressive regulation (a higher probability of enforcing a stricter standard for a given voluntary adoption level) affects innovation: More aggressive regulation encourages more firms to adopt a green technology once it is invented, but may discourage a firm from developing it if the competition intensity is high. Therefore, for technologies that attract a lot of additional demand in highly competitive industries, the government agency should be less aggressive in moving to a stricter standard to promote innovation. In some sense this gives the developing firm a larger potential window to enjoy the benefits of early development. This implication seems to be consistent with NHTSA's practice: Technologies to improve automobiles' fuel economies, like hybrid engines, can attract a significant number of consumers who are sensitive to fuel cost. Although such technologies had existed for a long time, NHTSA did not enforce a stricter standard on fuel economies until most major car manufacturers had developed such technologies (NHTSA 2009).

We also provide managerial insights for firms. When deciding on the development of a new technology, a firm should consider a relatively high payoff signal carefully because such a signal may indicate that competing firms will likewise adopt the technology and reduce the benefit of developing the technology. Our analysis also shows that uncertainty concerning the new technology's benefits can help motivate a firm to develop the new technology: When many adopters are anticipated, uncertainty may help soften competition by causing some firms to observe low signals. And when few adopters are anticipated, uncertainty may help increase the chance of regulation by causing some firms to observe high signals. Our analysis of the global game model helps understand interactions among firms' competition, government regulation, and uncertainty surrounding the benefits of a new green technology.

Acknowledgements

The authors sincerely appreciate helpful comments from the department editor, Vishal Gaur, the anonymous associate editor, and three reviewers. They are also grateful for helpful comments from Erica Plambeck and seminar participants at Carnegie Mellon University, Chinese University of Hong Kong, Shanghai University of Finance and Economics, Shanghai Jiao Tong University, Washington University in St. Louis, University of Texas at Dallas, Hong Kong University of Science and Technology, Hong Kong Polytechnic University, City University of Hong Kong, Wilfrid Laurier University, University of Pittsburgh, the INFORMS Annual Meeting, the MSOM Conference, and the POMS-HK International Conference. An earlier version of this paper was awarded the first prize in the 2019 INFORMS TIMES Best Working Paper Award Competition.

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Online Appendix for "Green Technology Development and Adoption: Competition, Regulation, and Uncertainty – A Global Game Approach"

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A Detailed Proofs

Proof of Lemma 1. We prove that a switching strategy around $x^{(2)}$ is an equilibrium by showing that if all firms but firm i follow this switching strategy, then firm i's best response is to follow this switching strategy. (In Lemma O1 of Online Appendix, we show how we derive this strategy using the argument of higher-order beliefs.)

We first derive firm i's expected gain $u_i(x_i)$ as a function of x_i, and then show that $u_i(x_i) \geq 0$ if and only if $x_i \geq x^{(2)}$. For notational convenience, define $\eta_i \equiv \frac{x_i - x^{(2)}}{2\epsilon}$. Given that every other firm follows a switching strategy around $x^{(2)}$, we can use get the expressions of α:

$$\alpha = \begin{cases} 0 & \text{if } \theta < x^{(2)} - \epsilon; \\ \frac{\theta + \epsilon - x^{(2)}}{2\epsilon} & \text{if } x^{(2)} - \epsilon \leq \theta \leq x^{(2)} + \epsilon; \\ 1 & \text{if } \theta > x^{(2)} + \epsilon. \end{cases} \tag{4}$$

We then use (4) to integrate $u_i(\theta, \alpha)$ in (1) to get the expression of $u_i(x_i)$. When $x_i < x^{(2)} - 2\epsilon$, we get $\alpha = 0$ and $u_i(x_i) = x_i - (1-q)(f_H - m_L) + f_H - f_L$. When $x^{(2)} - 2\epsilon \leq x_i \leq x^{(2)}$, we obtain the following expression of $u_i(x_i)$:

$$\begin{aligned} u_i(x_i) &= \int_{x_i - \epsilon}^{x_i + \epsilon} \frac{\theta}{2\epsilon} d\theta - (1-q)(f_H - m_L) + f_H - f_L \\ &\quad \frac{1}{2\epsilon} \int_{x^{(2)} - \epsilon}^{x_i + \epsilon} \left\{ (1-q)(f_H - m_L) \left(\frac{\theta + \epsilon - x^{(2)}}{2\epsilon} \right)^r - b \frac{\theta + \epsilon - x^{(2)}}{2\epsilon} \right\} d\theta \\ &= x_i - (1-q)(f_H - m_L) + f_H - f_L + \int_0^{\frac{x_1 + 2\epsilon - x^{(2)}}{2\epsilon}} \left\{ (1-q)(f_H - m_L)\alpha^r - b\alpha \right\} d\alpha, \end{aligned} \tag{5}$$

where the equality is obtained by changing the integration variable from θ to $\alpha = \frac{\theta + \epsilon - x^{(2)}}{2\epsilon}$. By using $\eta_i = \frac{x_i - x^{(2)}}{2\epsilon}$ (which is between -1 and 0 because $x^{(2)} - 2\epsilon \leq x_i \leq x^{(2)}$), we rewrite $u_i(x_i)$ in (5) as:

$$u_i\left(\eta_i\right) = x^{(2)} + 2\epsilon\eta_i - (1-q)\left(f_H - m_L\right) + f_H - f_L + \int_0^{1+\eta_i}\left\{-b\alpha + (1-q)\left(f_H - m_L\right)\alpha^r\right\}d\alpha.$$

Similarly, when $x^{(2)} < x_i \leq x^{(2)} + 2\epsilon$, we obtain

$$u_i\left(\eta_i\right) = x^{(2)} + 2\epsilon\eta_i - (1-q)\left(f_H - m_L\right) + f_H - f_L + \int_{\eta_i}^{1}\left\{-b\alpha + (1-q)\left(f_H - m_L\right)\alpha^r\right\}d\alpha + \eta_i\left\{(1-q)\left(f_H - m_L\right) - b\right\}.$$

When $x_i > x^{(2)} + 2\epsilon$, we obtain $u_i\left(x_i\right) = x_i - b + f_H - f_L$.

Next, we prove $u_i\left(x_i\right) \geq 0$ if and only if $x_i \geq x^{(2)}$ by showing: (i) $u_i\left(x^{(2)}\right) = 0$, and (ii) if $b \leq b^{(2)}$, then $u_i\left(x_i\right)$ is nondecreasing with x_i. To prove (i), from (5), we obtain $u_i\left(x^{(2)}\right) = x^{(2)} - (1-q)\left(f_H - m_L\right) + f_H - f_L - \frac{b}{2} + \frac{(1-q)(f_H - m_L)}{r+1}$. By substituting $x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}(1-q)\left(f_H - m_L\right)$ into $u_i\left(x^{(2)}\right)$, we get $u_i\left(x^{(2)}\right) = 0$.

To prove (ii), we derive conditions for $du_i\left(x_i\right)/dx_i \geq 0$ in each interval of x_i, and express those conditions as $b \leq b^{(2)}$. When $x_i < x^{(2)} - 2\epsilon$ or $x_i > x^{(2)} + 2\epsilon$, it is easy to show $du_i\left(x_i\right)/dx_i = 1 > 0$. When $x^{(2)} - 2\epsilon \leq x_i \leq x^{(2)}$, we analyze the sign of $du_i\left(\eta_i\right)/d\eta_i$ because $du_i\left(x_i\right)/dx_i = 2\epsilon du_i\left(\eta_i\right)/d\eta_i$ and $\epsilon > 0$. In preparation, we compute $\frac{du_i}{d\eta_i} = 2\epsilon - b\left(1+\eta_i\right) + (1-q)\left(f_H - m_L\right)\left(1+\eta_i\right)^r$, $\frac{d^2u_i}{d\eta_i^2} = -b + r(1-q)\left(f_H - m_L\right)\left(1+\eta_i\right)^{r-1}$, and $\frac{d^3u_i}{d\eta_i^3} = r(r-1)(1-q)\left(f_H - m_L\right)\left(1+\eta_i\right)^{r-2}$. First, consider the case when $r \leq 1$. Then $\frac{d^3u_i}{d\eta_i^3} \leq 0$ and $\frac{du_i}{d\eta_i}$ is concave. So if $\left.\frac{du_i}{d\eta_i}\right|_{\eta_i=-1} \geq 0$ and $\left.\frac{du_i}{d\eta_i}\right|_{\eta_i=0} \geq 0$, then $\frac{du_i}{d\eta_i} \geq 0$ for any $-1 \leq \eta_i \leq 0$. Since $\left.\frac{du_i}{d\eta_i}\right|_{\eta_i=-1} = 2\epsilon$ and $\left.\frac{du_i}{d\eta_i}\right|_{\eta_i=0} = 2\epsilon + (1-q)\left(f_H - m_L\right) - b$, $\frac{\partial u_i}{\partial\eta_i} \geq 0$ if $b \leq 2\epsilon + (1-q)\left(f_H - m_L\right)$. Second, consider the case when $r > 1$. Then $\frac{d^3u_i}{d\eta_i^3} > 0$, and $\frac{du_i}{d\eta_i}$ achieves its minimum value of $\left(\frac{du_i}{d\eta_i}\right)^{\min} = 2\epsilon + \left\{\frac{b}{r(1-q)(f_H - m_L)}\right\}^{\frac{1}{r-1}} b\left\{\frac{1}{r} - 1\right\}$ at $\eta_i^{\min} = \left\{\frac{b}{r(1-q)(f_H - m_L)}\right\}^{\frac{1}{r-1}} - 1$. If $r \geq \frac{b}{(1-q)(f_H - m_L)}$, then $-1 \leq \eta_i^{\min} \leq 0$ and $\frac{du_i}{d\eta_i} \geq 0$ if $\left(\frac{du_i}{d\eta_i}\right)^{\min} \geq 0$, which simplifies to $b \leq r\left(\frac{2\epsilon}{r-1}\right)^{1-\frac{1}{r}}\left\{(1-q)\left(f_H - m_L\right)\right\}^{\frac{1}{r}}$; otherwise, $\frac{du_i}{d\eta_i}$ is decreasing with $\eta_i \in [-1, 0]$, so $\frac{du_i}{d\eta_i} \geq 0$ if $\left.\frac{du_i}{d\eta_i}\right|_{\eta_i=0} \geq 0$, which simpilifies to $b \leq 2\epsilon + (1-q)\left(f_H - m_L\right)$. Following the same procedure as above, when $x^{(2)} < x_i \leq x^{(2)} + 2\epsilon$, we can obtain the condition for $\frac{du_i}{dx_i} \geq 0$ as follows: $b \leq 2\epsilon + (1-q)\left(f_H - m_L\right)$ if $r \geq \min\left\{1, \frac{b}{(f_H - m_L)(1-q)}\right\}$, and

$$\frac{1-r}{\left\{(1-q)\left(f_H - m_L\right)\right\}^{\frac{1}{r-1}}}\left(\frac{b}{r}\right)^{\frac{r}{r-1}} + b \leq 2\epsilon + (1-q)\left(f_H - m_L\right), \tag{6}$$

if $r < \min\left\{1, \frac{b}{(1-q)(f_H - m_L)}\right\}$. We can show that the left-hand side of (6) is increasing with b if $r < \min\left\{1, \frac{b}{(1-q)(f_H - m_L)}\right\}$ (see Lemma O2 for the proof). Thus, we can rewrite the condition in (6) as follows: $b \leq b^{(2)}$, where $b^{(2)}$ is the unique solution of $\frac{1-r}{\left\{(1-q)(f_H - m_L)\right\}^{\frac{1}{r-1}}}\left(\frac{b}{r}\right)^{\frac{r}{r-1}} + b = 2\epsilon + (1-q)\left(f_H - m_L\right)$. Finally, by combining the conditions for different intervals of x_i, we have

$\frac{du_i}{dx_i} \geq 0$ for any x_i if $b \leq b^{(2)}$, where

$$b^{(2)} = \begin{cases} \text{the solution of} & \\ \frac{1-r}{\{(1-q)(f_H-m_L)\}^{\frac{1}{r-1}}} \left(\frac{b}{r}\right)^{\frac{r}{r-1}} + b & \text{if } r < \min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}; \\ = 2\epsilon + (1-q)(f_H - m_L) & \\ 2\epsilon + (1-q)(f_H - m_L) & \text{if } \min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\} \leq r \leq \max\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}; \\ r\left(\frac{2\epsilon}{r-1}\right)^{1-\frac{1}{r}} \{(1-q)(f_H - m_L)\}^{\frac{1}{r}} & \text{if } r > \max\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}. \end{cases} \tag{7}$$

We show that $b^{(2)}$ in (7) is increasing with both ϵ and $f_H - m_L$ in Lemma O2. □

Lemma O1 *If $r \leq 1$ and $b \leq r(1-q)(f_H - m_L)$, then the equilibrium described in Lemma 1 is unique.*

Proof. Before we proceed to the proof, we first prove $u_i(\theta, \alpha)$ in (1) is increasing with θ and nondecreasing with α. From (1), $\partial u_i(\theta, \alpha)/\partial\theta = 1$ and thus $u_i(\theta, \alpha)$ is increasing with θ. In addition, we can get $\partial u_i(\theta, \alpha)/\partial\alpha = -b + r(1-q)(f_H - m_L)\alpha^{r-1}$. Since $0 \leq \alpha \leq 1$, $r \leq 1$, and $b \leq r(1-q)(f_H - m_L)$, we have $\partial u_i(\theta, \alpha)/\partial\alpha \geq 0$ and thus $u_i(\theta, \alpha)$ is nondecreasing with α.

We prove the argument in 3 steps. In step 1, we will prove by induction that a strategy survives n rounds of iterated deletion of strictly dominated strategies if and only if

$$a_i(x_i) = \begin{cases} 0 & \text{if } x_i < \underline{x}^{(n)}; \\ 1 & \text{if } x_i > \overline{x}^{(n)}. \end{cases} \tag{8}$$

In step 2, we prove $\underline{x}^{(n+1)} \geq \underline{x}^{(n)}$ and $\overline{x}^{(n+1)} \leq \overline{x}^{(n)}$ such that as $n \to \infty$, $\underline{x}^{(n)} \to \underline{x}$ and $\overline{x}^{(n)} \to \overline{x}$. In step 3, we finally prove $\underline{x} = \overline{x} = x^{(2)}$ such that the switching strategy around $x^{(2)}$ is the only strategy that survives iterated deletion of strictly dominated strategy.

Step 1: We first prove the statement holds for $\underline{x}^{(0)}$ and $\overline{x}^{(0)}$. Let $\overline{x}^{(0)} = b + (1-q)(f_H - m_L) - f_H + f_L + \epsilon$. Since $x_i = \theta + \widetilde{\varepsilon}_i$ and $\widetilde{\varepsilon}_i$ is uniformly distributed on $[-\epsilon, \epsilon]$, for any $x_i > \overline{x}^{(0)}$, $\theta > b + (1-q)(f_H - m_L) - f_H + f_L$ and from (1) $u_i(\theta, \alpha) > \alpha^r(1-q)(f_H - m_L) \geq 0$. So $a_i = 1$ for $x_i > \overline{x}^{(0)}$. Similarly, we let $\underline{x}^{(0)} = f_L - f_H - \epsilon$ and get the following: $a_i = 0$ if $x_i < \underline{x}^{(0)}$.

We next prove that a strategy that survives $n+1$ rounds of iterated deletion of strictly dominated strategies is in the form of (8); i.e., if firm i knows that other firms follow a strategy in the form of (8) with thresholds $\underline{x}^{(n)}$ and $\overline{x}^{(n)}$, then firm i's best response should be in the form of (8) with thresholds $\underline{x}^{(n+1)}$ and $\overline{x}^{(n+1)}$. Note that firm i expects $a_j = 1$ ($j \neq i$) for $x_j > \overline{x}^{(n)}$, and $a_j = 0$ ($j \neq i$) for $x_j < \underline{x}^{(n)}$. Firm i is not sure firm j's strategy for $\underline{x}^{(n)} \leq x_j \leq \overline{x}^{(n)}$. So the lowest value of α is achieved if $a_j = 0$ for any $x_j \in (\underline{x}^{(n)}, \overline{x}^{(n)})$. Since $u_i(\theta, \alpha)$ is nondecreasing with α, firm i expects the lowest gain in this case. It is easy to see that in this case other firms follow a switching strategy around $\overline{x}^{(n)}$. Define $u_i^*(x_i, x)$ the expected value of $u_i(\theta, \alpha)$ given that firm i observes x_i and any other firm will follow a switching strategy around x. Then $u_i^*\left(x_i, \overline{x}^{(n)}\right)$ is the lower bound of firm i's expected gain. If $u_i^*\left(x_i, \overline{x}^{(n)}\right) > 0$, then firm i chooses $a_i = 1$ if observing x_i. Let $\overline{x}^{(n+1)}$ be the solution of $u^*\left(x_i, \overline{x}^{(n)}\right) = 0$. Following a similar procedure to that in the proof of Lemma 1, we can show that $u^*\left(x_i, \overline{x}^{(n)}\right)$ is increasing with x_i. So $a_i = 1$ for any $x_i > \overline{x}^{(n+1)}$. Similarly, $u_i^*\left(x_i, \underline{x}^{(n)}\right)$ is the upper bound of firm i's expected gain. Let $\underline{x}^{(n+1)}$ be the solution of $u^*\left(x_i, \underline{x}^{(n)}\right) = 0$. Then $a_i = 0$ for any $x_i < \underline{x}^{(n+1)}$.

Step 2: We prove $\underline{x}^{(n+1)} \geq \underline{x}^{(n)}$ and $\overline{x}^{(n+1)} \leq \overline{x}^{(n)}$ by induction. Since we have shown that $u^*(x_i, x)$ increases with x_i and $u^*\left(\overline{x}^{(1)}, \overline{x}^{(0)}\right) = 0$, we need to show $u^*\left(\overline{x}^{(0)}, \overline{x}^{(0)}\right) \geq 0$ to prove $\overline{x}^{(1)} \leq \overline{x}^{(0)}$. Following a similar procedure to that in the proof of Lemma 1, we get

$$u^*(x, x) = x - \frac{b}{2} - f_L + f_H - \frac{r}{r+1}(1-q)(f_H - m_L). \tag{9}$$

Using $\overline{x}^{(0)} = b + (1-q)(f_H - m_L) - f_H + f_L + \epsilon$ we get $u^*\left(\overline{x}^{(0)}, \overline{x}^{(0)}\right) = \frac{1}{r+1}(1-q)(f_H - m_L) + \frac{b}{2} + \epsilon > 0$. Similarly, we get $\underline{x}^{(1)} \geq \underline{x}^{(0)}$.

We next show $\overline{x}^{(n+1)} \leq \overline{x}^{(n)}$ given that $\overline{x}^{(n)} \leq \overline{x}^{(n-1)}$. Following a similar procedure to that in the proof of Lemma 1, we can show that $u^*(x_i, x)$ is decreasing with x. Since $u^*\left(\overline{x}^{(n)}, \overline{x}^{(n-1)}\right) = 0$ and $\overline{x}^{(n)} \leq \overline{x}^{(n-1)}$, we get $u^*\left(\overline{x}^{(n)}, \overline{x}^{(n)}\right) \geq 0$. Since $u^*(x_i, x)$ increases with x_i, $u^*\left(\overline{x}^{(n+1)}, \overline{x}^{(n)}\right) = 0$, and $u^*\left(\overline{x}^{(n)}, \overline{x}^{(n)}\right) \geq 0$, we get $\overline{x}^{(n+1)} \leq \overline{x}^{(n)}$. Similarly, we obtain the following: $\underline{x}^{(n+1)} \geq \underline{x}^{(n)}$ given that $\underline{x}^{(n)} \geq \underline{x}^{(n-1)}$.

Step 3: As $n \to \infty$, $\underline{x}^{(n)} \to \underline{x}$ and $\overline{x}^{(n)} \to \overline{x}$, where $u^*(\underline{x}, \underline{x}) = 0$ and $u^*(\overline{x}, \overline{x}) = 0$. From (9) we can show that $x^{(2)}$ is the unique solution to $u^*(x, x) = 0$. Thus $\underline{x} = \overline{x} = x^{(2)}$. □

Remark 1. The proof of Lemma O1 uses an argument of iterated deletion of strictly dominated strategies. This argument was used in Morris and Shin (2003) to derive a unique equilibrium when only strategic complementarity among firms is present. This process can also be viewed as a process in which firm i considers its higher-order beliefs to eliminate possible strategies. First, firm i considers its own signal and gets a strategy specified by (8) with thresholds $\underline{x}^{(0)}$ and $\overline{x}^{(0)}$. Then by considering its belief that all other firms follow a strategy specified by (8) with thresholds $\underline{x}^{(0)}$ and $\overline{x}^{(0)}$, firm i refines its strategy and gets a strategy specified by (8) with thresholds $\underline{x}^{(1)}$ and $\overline{x}^{(1)}$. Next by considering its belief about other firms' strategy with $\underline{x}^{(1)}$ and $\overline{x}^{(1)}$, firm i gets a strategy with thresholds $\underline{x}^{(1)}$ and $\overline{x}^{(1)}$. This process continues and finally firm i gets a switching strategy with a threshold $x^{(2)}$.

We use an argument of iterated deletion of strictly dominated strategies to derive the equilibrium strategy in Lemma 1 (a switching strategy around $x^{(2)}$) and prove the uniqueness of this equilibrium under the condition $r \leq 1$ and $b \leq r(1-q)(f_H - m_L)$. We show in Lemma 1 that this switching strategy continues to be an equilibrium strategy for every firm under a more general condition. Similarly, Karp et al. (2007) proved that every firm following a switching strategy is an equilibrium in a one-period setting with both strategic complementarity and substitutability.

Remark 2. In the proof of Lemma O1, we used the property that $u_i(\theta, \alpha)$ is nondecreasing with α under the conditions $r \leq 1$ and $b \leq r(1-q)(f_H - m_L)$. This property enables us to use the argument of iterated deletion of strictly dominated strategies: In every iteration we can obtain new thresholds $\underline{x}^{(n+1)}$ and $\overline{x}^{(n+1)}$ from previous thresholds $\underline{x}^{(n)}$ and $\overline{x}^{(n)}$, where $\underline{x}^{(n+1)} \geq \underline{x}^{(n)}$ and $\overline{x}^{(n+1)} \leq \overline{x}^{(n)}$. However, if the conditions $r \leq 1$ and $b \leq r(1-q)(f_H - m_L)$ are not satisfied, this property does not hold and we cannot use the same argument. Since the action space is not continuous, other standard approach such as the contraction mapping method cannot be used, either.

It is well-known that finding equilibria in games of incomplete information with finite actions and continuous types is quite difficult, let alone proving the uniqueness (Rabinovich et al. 2013). A common approach in literature (e.g., Karp et al. 2007, Rabinovich et al. 2013) is to use a numerical analysis to verify uniqueness. Similarly, we conduct a numerical experiment to find all possible equilibria. Since there are an infinite number of possible asymmetric equilibria among a continuum of firms, we focus on symmetric equilibria in our numerical experiment. From (1), we can show that firm i does not adopt the technology regardless of other firms' decisions if $\theta < f_L - f_H$, and that firm i adopts the technology regardless of other firms' decisions if $\theta > b + f_L - m_L$. Therefore, we focus on $\theta \in [f_L - f_H, b + f_L - m_L]$. To ensure the existence of an equilibrium, we set $b \leq b^{(2)}$, which is the existence condition provided in Lemma 1. Following Karp et al. (2007), we use a finite-state approximation to obtain possible equilibria in period 2, including pure strategy and mixed strategy equilibria. To approximate the continuous state of θ, we assume that θ can take N possible values θ_1, θ_2, ..., θ_N, where $\theta_j = f_L - f_H + \frac{j-1}{N-1}(b + f_H - m_L)$. The signal x_i can take any of the M values above and below a θ value with equal probability, where $M = \lceil \frac{\epsilon}{b+f_H-m_L} N \rceil$ reflects the magnitude of noise.

We next describe the algorithm to find all possible equilibria. Let p_j denote the probability that a firm adopts the technology if the firm observes a signal with the value θ_j. Define $\mathbf{p} \equiv (p_1, p_2, ..., p_N)$. The vector $\mathbf{p}$ specifies a strategy for a firm. Let $u(\mathbf{p}, \theta_j)$ denote a firm's expected gain of adopting the technology when the firm observes a signal with value θ_j and all firms follow the strategy $\mathbf{p}$. The strategy $\mathbf{p}$ is an equilibrium if and only if the following statement holds: If $p_j = 0$, then $u(\mathbf{p}, \theta_j) \leq 0$; if $0 < p_j < 1$, then $u(\mathbf{p}, \theta_j) = 0$ (the condition $0 < p_j < 1$ implies a mixed strategy, which is possible only if $u(\mathbf{p},\theta_j) = 0$); or if $p_j = 1$, then $u(\mathbf{p},\theta_j) \geq 0$. This statement can be rewritten as the following nonlinear complementarity problem: Find a vector $\mathbf{p}$ (where $p_j \in [0,1]$) such that the following conditions are met: $p_j < 1 \Rightarrow u(\mathbf{p},\theta_j) \leq 0$, and $p_j > 0 \Rightarrow u(\mathbf{p},\theta_j) \geq 0$. We solve this nonlinear complementarity problem using the Matlab toolbox provided by Miranda and Fackler (2002). We refer interested readers to Miranda and Fackler (2002) for details about the complementarity problem and the toolbox.

We conduct a numerical experiment using the following parameter values: $r \in \{0.3, 0.5, 1, 2, 3\}$, $m_L \in \{-1, -2, -3\}$, $f_H \in \{1, 2, 3\}$, $f_L \in \{0.2f_H, 0.5f_H, 0.8f_H\}$, $\epsilon \in \{0.1(f_H - m_L), 0.2(f_H - m_L), 0.3(f_H - m_L)\}$, $b \in \{0.1b^{(2)}, 0.4b^{(2)}, 0.7b^{(2)}, b^{(2)}\}$, $q \in \{0, 0.2, 0.4\}$, and $N = 50$. We use $N = 50$ to achieve a balance between computational speed and accuracy. We do not include λ and f_1 because they do not appear in (1) and they do not affect the equilibrium in period 2. For each instance, we use a random generated vector $\mathbf{p}$ as the starting value for the solver. If the solver does not converge, we generate another random vector and start again. In all the 4860 instances, we only find one equilibrium in which firms follow a threshold strategy. Therefore, we numerically verify that if the existence condition in Lemma 1 is satisfied, there is a unique symmetric equilibrium.

Lemma O2 *The threshold $b^{(2)}$ is increasing with ϵ and $(f_H - m_L)$.*

Proof. From (7) it is straight forward that $b^{(2)}$ is increasing with ϵ and $(f_H - m_L)$ if $r > \max\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}$ or $\min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\} \leq r \leq \max\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}$. For the case in which $r < \min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}$, $b^{(2)}$ is defined as the solution to $g(b) = 0$, where $g(b) = \frac{1-r}{\{(1-q)(f_H-m_L)\}^{\frac{1}{r-1}}}\left(\frac{b}{r}\right)^{\frac{r}{r-1}} + b - 2\epsilon - (1-q)(f_H - m_L)$. Using the implicit function theorem, we have that $\frac{db^{(2)}}{d\epsilon} = -\frac{\partial g/\partial \epsilon}{\partial g/\partial b}$ and $\frac{db^{(2)}}{d(f_H-m_L)} = -\frac{\partial g/\partial (f_H-m_L)}{\partial g/\partial b}$. We next show that $\partial g/\partial \epsilon < 0$, $\partial g/\partial b > 0$, and $\partial g/\partial (f_H - m_L) < 0$ such that $b^{(2)}$ is increasing with ϵ and $(f_H - m_L)$. It is easy to show $\partial g/\partial \epsilon = -2 < 0$. We can calculate $\partial g/\partial b$ as follow: $\frac{\partial g}{\partial b} = -\left\{\frac{b}{r(1-q)(f_H-m_L)}\right\}^{\frac{1}{r-1}} + 1$. Since $r < \min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}$, we have $\frac{b}{r(1-q)(f_H-m_L)} > 1$ and $\frac{1}{r-1} < 0$. So $\left\{\frac{b}{(1-q)(f_H-m_L)r}\right\}^{\frac{1}{r-1}} < 1$ and $\frac{\partial g}{\partial b} = -\left\{\frac{b}{(1-q)(f_H-m_L)r}\right\}^{\frac{1}{r-1}} + 1 > 0$. Finally, we obtain the expression of $\partial g/\partial (f_H - m_L)$: $\frac{\partial g}{\partial (f_H-m_L)} = (1-q)\left\{\frac{b}{r(1-q)(f_H-m_L)}\right\}^{\frac{r}{r-1}} - (1-q)$. Similar to the proof of $\partial g/\partial b > 0$ we can show that $\partial g/\partial (f_H - m_L) < 0$. $\square$

Proof of Proposition 1. Since $x_1 = \theta + \widetilde{\varepsilon}_1$, for any given x_1, the posterior distribution of θ is a uniform distribution on $[x_1 - \epsilon, x_1 + \epsilon]$. Since $\widetilde{\varepsilon}_i$ is independent of $\widetilde{\varepsilon}_1$, it is also independent of θ. Thus, $x_i = \theta + \widetilde{\varepsilon}_i$ is a sum of two uniformly distributed random variables that are independent. Using convolution, we can show that the posterior distribution of x_i for any given x_1 is a symmetric triangular distribution on $[x_1 - 2\epsilon, x_1 + 2\epsilon]$. Using this result, we next prove (a) and (b).

(a) Following the same procedure as in the proof of Lemma 1, we obtain the expression of $u_1(x_1)$ as follows:

$$u_1(x_1) = \begin{cases} \lambda - f_1 + m_L + q(m_H - m_L) + x_1 & \text{if } x_1 \le x^{(2)} - 2\epsilon; \\ \lambda - f_1 + m_L + q(m_H - m_L) + x_1 - \frac{b}{2}\left(\frac{x_1 - x^{(2)} + 2\epsilon}{2\epsilon}\right)^2 & \text{if } x^{(2)} - 2\epsilon < x_1 < x^{(2)}; \\ \lambda - f_1 + m_L + q(m_H - m_L) + x_1 \\ \quad -\frac{b}{2}\left\{1 - \left(\frac{x_1 - x^{(2)}}{2\epsilon}\right)^2\right\} - b\left(\frac{x_1 - x^{(2)}}{2\epsilon}\right) & \text{if } x^{(2)} \le x_1 < x^{(2)} + 2\epsilon; \\ \lambda - f_1 + m_H + x_1 - b & \text{if } x_1 \ge x^{(2)} + 2\epsilon. \end{cases} \tag{10}$$

Using (10), we obtain the expression of $\frac{\partial u_1}{\partial x_1}$:

$$\frac{du_1(x_1)}{dx_1} = \begin{cases} 1 & \text{if } x_1 \le x^{(2)} - 2\epsilon; \\ 1 - \frac{b}{2\epsilon}\left(\frac{x_1 - x^{(2)} + 2\epsilon}{2\epsilon}\right) & \text{if } x^{(2)} - 2\epsilon < x_1 < x^{(2)}; \\ 1 - \frac{b}{2\epsilon}\left(\frac{2\epsilon - x_1 + x^{(2)}}{2\epsilon}\right) & \text{if } x^{(2)} \le x_1 < x^{(2)} + 2\epsilon; \\ 1 & \text{if } x_1 \ge x^{(2)} + 2\epsilon. \end{cases} \tag{11}$$

We next consider two cases: $\epsilon \ge b/2$ and $\epsilon < b/2$.

For the case of $\epsilon \ge b/2$, from (11) $\frac{\partial u_1}{\partial x_1} \ge 0$. So u_1 crosses zero only once. Let $x_{subs}^{(1)}$ be the solution of $u_1(x_1)$. Then $u_1(x_1) > 0$ if and only if $x_1 > x_{subs}^{(1)}$.

For the case of $\epsilon < b/2$, we will first prove that u_1 increases with x_1, then decreases with x_1, and finally increases with x_1 again. We then compare the local maximum and minimum of u_1 with 0 to determine firm 1's decision. First, we show the shape of u_1 on $\left[x^{(2)} - 2\epsilon, x^{(2)}\right]$. From (11), $\left.\frac{\partial u_1}{\partial x_1}\right|_{x_1 = x^{(2)} - 2\epsilon} > 0$, $\left.\frac{\partial u_1}{\partial x_1}\right|_{x_1 = x^{(2)}} < 0$, and $\frac{\partial^2 u_1}{\partial x_1^2} = -\frac{b}{(2\epsilon)^2} < 0$ when $x^{(2)} - 2\epsilon \le x_1 < x^{(2)}$. Therefore, There exists $x_1^M \in \left(x^{(2)} - 2\epsilon, x^{(2)}\right)$ such that at $x_1 = x_1^M$, $\frac{\partial u_1}{\partial x_1} = 0$ and $u_1(x_1)$ achieves its local maximum $u_1(x_1^M)$. Solving $\frac{\partial u_1}{\partial x_1} = 0$ in this case yields $x_1^M = x^{(2)} - 2\epsilon + \frac{(2\epsilon)^2}{b}$. Substituting this expression to (10) we obtain $u_1(x_1^M) = \lambda - f_1 + m_L + q(m_H - m_L) + x^{(2)} - 2\epsilon + \frac{2\epsilon^2}{b}$. Similarly, from (11) we get $\left.\frac{\partial u_1}{\partial x_1}\right|_{x_1 = x^{(2)}} < 0$, $\left.\frac{\partial u_1}{\partial x_1}\right|_{x_1 = x^{(2)} + 2\epsilon} > 0$, and $\frac{\partial^2 u_1}{\partial x_1^2} = \frac{b}{(2\epsilon)^2} > 0$ when $x^{(2)} \le x_1 \le x^{(2)} + 2\epsilon$. So there exists $x_1^m \in \left(x^{(2)}, x^{(2)} + 2\epsilon\right)$ such that at $x_1 = x_1^m$, $\frac{\partial u_1}{\partial x_1} = 0$ and $u_1(x_1)$ achieves its local minimum value $u_1(x_1^m) = \lambda - f_1 + m_L + q(m_H - m_L) + x^{(2)} + 2\epsilon - b - \frac{2\epsilon^2}{b}$.

We next analyze three cases: (Case I) $u_1(x_1^M) < 0$, (Case II) $u_1(x_1^m) > 0$, and (Case III) $u_1(x_1^m) \le 0$ and $u_1(x_1^M) \ge 0$.

(Case I) From the expression of $u_1(x_1^M)$, $u_1(x_1^M) < 0$ when $\lambda < -x^{(2)} + 2\epsilon - \frac{2\epsilon^2}{b} + f_1 - m_L - q(m_H - m_L)$. Let $\underline{\lambda}_{subs} = -x^{(2)} + 2\epsilon - \frac{2\epsilon^2}{b} + f_1 - m_L - q(m_H - m_L)$. Then $u_1(x_1^M) < 0$ if and only if $\lambda < \underline{\lambda}_{subs}$. In this case, given that the local maximum $u_1(x_1^M) < 0$, $u_1(x_1)$ can cross zero once in the interval (x_1^m, ∞). Denote by $x_{subs}^{(1)}$ the solution of $u_1(x_1) = 0$. Then $u_1(x_1) > 0$ if and only if $x_1 > x_{subs}^{(1)}$.

(Case II) Similar to (Case I), we can show $u_1(x_1^m) > 0$ when $\lambda > \overline{\lambda}_{subs}$, where $\overline{\lambda}_{subs} = -x^{(2)} - 2\epsilon + b + \frac{2\epsilon^2}{b} + f_1 - m_L - q(m_H - m_L)$. There exists $x_{subs}^{(1)} < x_1^m$ such that $u_1(x_1) > 0$ if and only if $x_1 > x_{subs}^{(1)}$.

(Case III) Similarly, $u_1(x_1^m) \leq 0$ and $u_1(x_1^M) \geq 0$ when $\underline{\lambda}_{subs} \leq \lambda \leq \overline{\lambda}_{subs}$. We can prove that there exists $x_{subs}^{(1)}$, $y_{subs}^{(1)}$, and $z_{subs}^{(1)}$ ($x_{subs}^{(1)} \leq x_1^M \leq y_{subs}^{(1)} \leq x_1^m \leq z_{subs}^{(1)}$) such that $u_1(x_1) \geq 0$ if and only if $x_1 \in [x_{subs}^{(1)}, y_{subs}^{(1)}] \cup [z_{subs}^{(1)}, \infty)$.

(b) In order to compute $\frac{dx_{subs}^{(1)}}{dr}$, we apply the implicit function theorem to the equation $u_1(x_1) = 0$ and obtain the following: $\frac{dx_{sub}^{(1)}}{dr} = -\left.\frac{\partial u_1/\partial r}{\partial u_1/\partial x_1}\right|_{x_1 = x_{subs}^{(1)}}$. From the proof of part (a), $\left.\frac{\partial u_1}{\partial x_1}\right|_{x_1 = x_{subs}^{(1)}} > 0$ and $\frac{dx^{(1)}}{dr}$ has the same sign as $-\left.\frac{\partial u_1}{\partial r}\right|_{x_1 = x_{subs}^{(1)}}$. We examine the sign of $\left.\frac{\partial u_1}{\partial r}\right|_{x_1 = x_{subs}^{(1)}}$ in the following four cases: (Case I) $x_{subs}^{(1)} < x^{(2)} - 2\epsilon$, (Case II) $x^{(2)} - 2\epsilon \leq x_{subs}^{(1)} \leq x^{(2)}$, (Case III) $x^{(2)} < x_{subs}^{(1)} \leq x^{(2)} + 2\epsilon$, and (Case IV) $x_{subs}^{(1)} > x^{(2)} + 2\epsilon$.

(Cases I and IV) From (10), we obtain $\frac{\partial u_1}{\partial r} = 0$. So $\frac{dx_{sub}^{(1)}}{dr} = 0$ and $x_{sub}^{(1)}$ is independent of r.

(Case II) From (10) and $x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}(1-q)(f_H - m_L)$ in Lemma 1, we obtain $\frac{\partial u_1}{\partial r} = \frac{\partial u_1}{\partial x^{(2)}}\frac{\partial x^{(2)}}{\partial r} = \frac{b}{2\epsilon}\left(\frac{x_1 - x^{(2)} + 2\epsilon}{2\epsilon}\right)\frac{(1-q)(f_H - m_L)}{(r+1)^2} > 0$. So $\frac{dx_{sub}^{(1)}}{dr} < 0$.

(Case III) Similar to Case II, we obtain $\frac{\partial u_1}{\partial r} = \frac{b}{2\epsilon}\left\{1 - \left(\frac{x_1 - x^{(2)}}{2\epsilon}\right)\right\}\frac{(1-q)(f_H - m_L)}{(r+1)^2} > 0$. So $\frac{dx_{sub}^{(1)}}{dr} < 0$. Following the same procedure, we can prove the results for $y_{subs}^{(1)}$ and $z_{subs}^{(1)}$.

(c) Similar to part (b), the sign of $\frac{dx_{subs}^{(1)}}{d\epsilon}$ is the same as $-\left.\frac{\partial u_1}{\partial \epsilon}\right|_{x_1 = x_{subs}^{(1)}}$. We check the same four cases as in part (b).

(Cases I and IV) From (10), we obtain $\frac{\partial u_1}{\partial \epsilon} = 0$. So $x_{sub}^{(1)}$ is independent of ϵ.

(Case II) From (10) we obtain $\frac{\partial u_1}{\partial \epsilon} = b\left(\frac{x_1 - x^{(2)}}{2\epsilon} + 1\right)\left(\frac{x_1 - x^{(2)}}{2\epsilon^2}\right) \leq 0$ when $x_1 = x_{subs}^{(1)} \in [x^{(2)} - 2\epsilon, x^{(2)})$. So $\frac{dx_{sub}^{(1)}}{d\epsilon} \geq 0$.

(Case III) Similar to Case II, we obtain $\frac{\partial u_1}{\partial \epsilon} = b\left(\frac{x_1 - x^{(2)}}{2\epsilon^2}\right)\left(1 - \frac{x_1 - x^{(2)}}{2\epsilon}\right) \geq 0$ when $x_1 = x_{subs}^{(1)} \in [x^{(2)}, x^{(2)} + 2\epsilon]$. So $\frac{dx_{sub}^{(1)}}{d\epsilon} \leq 0$.

Following the same procedure, we can prove the results for $y_{subs}^{(1)}$ and $z_{subs}^{(1)}$. □

Proof of Proposition 2. Following the same procedure as in the proof of Lemma 1, we obtain the expression of $\frac{\partial u_1}{\partial x_1}$ as follows:

$$\frac{du_1(x_1)}{dx_1} = \begin{cases} 1 & \text{if } x_1 < x^{(2)} - 2\epsilon; \\ 1 + \frac{(1-q)(m_H - m_L)}{2\epsilon}\left(\frac{x_1 - x^{(2)} + 2\epsilon}{2\epsilon}\right)^r & \text{if } x^{(2)} - 2\epsilon \leq x_1 < x^{(2)}; \\ 1 + \frac{(1-q)(m_H - m_L)}{2\epsilon}\left\{1 - \left(\frac{x_1 - x^{(2)}}{2\epsilon}\right)^r\right\} & \text{if } x^{(2)} \leq x_1 \leq x^{(2)} + 2\epsilon; \\ 1 & \text{if } x_1 > x^{(2)} + 2\epsilon. \end{cases} \tag{12}$$

We can verify that $\frac{\partial u_1}{\partial x_1} > 0$ in all intervals. So u_1 crosses zero only once. Let $x_{comp}^{(1)}$ be the solution of $u_1(x_1) = 0$. Then $u_1(x_1) > 0$ if and only if $x_1 > x_{comp}^{(1)}$.

(b) and (c) The proof follows the same procedure as in the proof of Proposition 1(b) and (c), respectively. □

Proof of Proposition 3. **(a)** Similar to the proof of Proposition 1(a), we can show that there are two cases. In the first case, $u_1(x_1)$ is nondecreasing with x_1, and there exists threshold $x_{aggr}^{(1)}$ such that $u_1(x_1) > 0$ if and only if $x_1 > x_{aggr}^{(1)}$. In the second case, $u_1(x_1)$ first increases with x_1, then decreases with x_1, and finally increases with x_1 again. In this case, there exists $x_1^M < x_1^m$ such that $u_1(x_1)$ achieves a local maximum at x_1^M and a local minimum at x_1^m. If $u_1\left(x_1^M\right) < 0$ or $u_1(x_1^m) > 0$, then there exists threshold $x_{aggr}^{(1)}$ such that $u_1(x_1) > 0$ if and only if $x_1 > x_{aggr}^{(1)}$. If $u_1\left(x_1^M\right) \geq 0$ and $u_1(x_1^m) \leq 0$, then there exists $x_{aggr}^{(1)} \leq x_1^M \leq y_{aggr}^{(1)} \leq x_1^m \leq z_{aggr}^{(1)}$ such that $u_1(x_1) \geq 0$ if and only if $x_1 \in [x_{aggr}^{(1)}, y_{aggr}^{(1)}] \cup [z_{aggr}^{(1)}, \infty)$. We let $\underline{\lambda}_{aggr}$ be the value of λ such that $u_1\left(x_1^M\right) = 0$ if $\lambda = \underline{\lambda}_{aggr}$, and $\overline{\lambda}_{aggr}$ be the value of λ such that $u_1(x_1^m) = 0$ if $\lambda = \overline{\lambda}_{aggr}$. Then $u_1\left(x_1^M\right) \geq 0$ and $u_1(x_1^m) \leq 0$ if and only if $\underline{\lambda}_{aggr} \leq \lambda \leq \overline{\lambda}_{aggr}$.

Finally, we show in Lemma O3 that the first case (respectively, the second case) occurs if $b \leq b^{(1)}$ (respectively, $b > b^{(1)}$), where

$$b^{(1)} = \begin{cases} \text{the solution of} & \\ \frac{1-r}{\{(1-q)(m_H-m_L)\}^{\frac{1}{r-1}}} \left(\frac{b}{r}\right)^{\frac{r}{r-1}} + b & \text{if } r < \min\left\{1, \frac{b}{(1-q)(m_H-m_L)}\right\}; \\ = 2\epsilon + (1-q)(m_H - m_L) & \\ 2\epsilon + (1-q)(m_H - m_L) & \text{if } \min\left\{1, \frac{b}{(1-q)(m_H-m_L)}\right\} \leq r \leq \max\left\{1, \frac{b}{(1-q)(m_H-m_L)}\right\}; \\ r\left(\frac{2\epsilon}{r-1}\right)^{1-\frac{1}{r}} \{(1-q)(m_H-m_L)\}^{\frac{1}{r}} & \text{if } r > \max\left\{1, \frac{b}{(1-q)(m_H-m_L)}\right\}. \end{cases} \tag{13}$$

Similar to Lemma 1, we can show that $b^{(1)}$ is increasing with both ϵ and $m_H - m_L$.

(b) As in the proof of Proposition 1(b), we can show that $\frac{dx_{aggr}^{(1)}}{dr}$ has the same sign as $-\left.\frac{\partial u_1}{\partial r}\right|_{x_1 = x_{aggr}^{(1)}}$. We examine the sign of $\left.\frac{\partial u_1}{\partial r}\right|_{x_1 = x_{aggr}^{(1)}}$ in the following four cases: (Case I) $x_{aggr}^{(1)} < x^{(2)} - 2\epsilon$, (Case II) $x^{(2)} - 2\epsilon \leq x_{aggr}^{(1)} \leq x^{(2)}$, (Case III) $x^{(2)} < x_{aggr}^{(1)} \leq x^{(2)} + 2\epsilon$, and (Case IV) $x_{aggr}^{(1)} > x^{(2)} + 2\epsilon$. To do so, we write the expression of $u_1(x_1)$ as follows: Following the same procedure as in the proof of Lemma 1, we obtain the expression of $u_1(x_1)$ as follows:

$$u_1(x_1) = \begin{cases} \lambda - f_1 + m_L + q(m_H - m_L) + x_1 & \text{if } x_1 < x^{(2)} - 2\epsilon; \\ \lambda - f_1 + m_L + q(m_H - m_L) + x_1 - \frac{b}{2}(1+\eta_1)^2 \\ \quad + \frac{(1-q)(m_H - m_L)}{r+1}(1+\eta_1)^{r+1} & \text{if } x^{(2)} - 2\epsilon \le x_1 \le x^{(2)}; \\ \lambda - f_1 + m_L + q(m_H - m_L) + x_1 - \frac{b}{2}\left(1 - \eta_1^2\right) \\ \quad + \frac{(1-q)(m_H - m_L)}{r+1}\left(1 - \eta_1^{r+1}\right) + \{(1-q)(m_H - m_L) - b\}\eta_1 & \text{if } x^{(2)} \le x_1 \le x^{(2)} + 2\epsilon; \\ \lambda - f_1 + m_H + x_1 - b, & \text{if } x_1 > x^{(2)} + 2\epsilon, \end{cases} \tag{14}$$

where $\eta_1 = \frac{x_1 - x^{(2)}}{2\epsilon}$. We next check the four cases.

(Cases I and IV) From (14), $\frac{\partial u_1}{\partial r} = 0$. So $\frac{dx_{aggr}^{(1)}}{dr} = 0$ and $x_{aggr}^{(1)}$ is independent of r.

(Case II) From (15) and $x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}(1-q)(f_H - m_L)$ in Lemma 1, we obtain the following:

$$\frac{du_1}{dr} = \frac{\partial u_1}{\partial r} + \frac{\partial u_1}{\partial x^{(2)}}\frac{\partial x^{(2)}}{\partial r} + \frac{\partial u_1}{\partial \eta_1}\frac{\partial \eta_1}{\partial x^{(2)}}\frac{\partial x^{(2)}}{\partial r}$$
$$= \frac{(1-q)(1+\eta_1)}{r+1}\left[-(m_H - m_L)(1+\eta_1)^{r-1}\left\{\frac{1+\eta_1}{r+1} - (1+\eta_1)\ln(1+\eta_1) + \frac{(f_H - m_L)(1-q)}{2\epsilon(r+1)}\right\} + \frac{(f_H - m_L)b}{2\epsilon(r+1)}\right].$$

Let $b_x^* = (m_H - m_L)\left(1+\eta_{aggr}\right)^{r-1}\left\{\frac{2\epsilon\left(1+\eta_{aggr}\right)}{f_H - m_L} - \frac{2\epsilon(r+1)\left(1+\eta_{aggr}\right)}{f_H - m_L}\ln\left(1+\eta_{aggr}\right) + 1 - q\right\}$, where $\eta_{aggr} = \frac{x_{aggr}^{(1)} - x^{(2)}}{2\epsilon}$. Finally, from the above equation, we get $\frac{du_1}{dr} > 0$, and thus $\frac{dx_{aggr}^{(1)}}{dr} < 0$ if and only if $b > b_x^*$.

(Case III) Similar to (Case II), we can show that $\frac{dx_{aggr}^{(1)}}{dr} < 0$ if and only if $b > b_x^*$, where $b_x^* = \frac{m_H - m_L}{1-\eta_{aggr}}\left\{\frac{2\epsilon\left(1-\eta_{aggr}^{r+1}\right)}{f_H - m_L} + \frac{2\epsilon(r+1)\eta_{aggr}^{r+1}}{f_H - m_L}\ln\eta_{aggr} + (1-q)\left(1-\eta_{aggr}^r\right)\right\}$.

Following the same procedure, we can prove the results for $y_{aggr}^{(1)}$ and $z_{aggr}^{(1)}$.

(c) Similar to part (b), we can show that $\frac{dx_{aggr}^{(1)}}{d\epsilon}$ has the same sign as $-\left.\frac{\partial u_1}{\partial \epsilon}\right|_{x_1 = x_{aggr}^{(1)}}$. We examine the sign of $\left.\frac{\partial u_1}{\partial \epsilon}\right|_{x_1 = x_{aggr}^{(1)}}$ in the same four cases:

(Cases I and IV) From (14), $\frac{\partial u_1}{\partial \epsilon} = 0$ and $x_{aggr}^{(1)}$ is independent of ϵ.

(Case II) From (14) we obtain the following

$$\frac{du_1}{d\epsilon} = \frac{du_1}{d\eta_1}\frac{\partial \eta_1}{\partial \epsilon} = \left\{-b(1+\eta_1) + (1-q)(m_H - m_L)(1+\eta_1)^r\right\}\left(\frac{x^{(2)} - x_1}{2\epsilon^2}\right).$$

Let $b_x^{**} = (1-q)(m_H - m_L)\left(1+\eta_{aggr}\right)^{r-1}$. From the above equation, we get $\frac{du_1}{d\epsilon} \le 0$, and thus $\frac{dx_{aggr}^{(1)}}{d\epsilon} \ge 0$ if and only if $b > b_x^{**}$.

(Case III) Similar to (Case II), we can show that $\frac{dx_{aggr}^{(1)}}{d\epsilon} < 0$ if and only if $b > b_x^{**}$, where $b_x^{**} = (1-q)(m_H - m_L)\frac{1-\eta_{aggr}^r}{1-\eta_{aggr}}$.

Following the same procedure, we can prove the results for $y_{aggr}^{(1)}$ and $z_{aggr}^{(1)}$. □

Lemma O3 *If $b \le b^{(1)}$, where $b^{(1)}$ is given in (13), then $u_1(x_1)$ increases with x_1. Otherwise $u_1(x_1)$ first increases with x_1, then decreases with x_1, and finally increases with x_1 again.*

Proof. From (14), it is easy to observe that $u_1(x_1)$ is increasing with x_1 in the first and last intervals of x_1. We focus our analysis on the two middle intervals. Let $\eta_1 = \frac{x_1 - x^{(2)}}{2\epsilon}$ and

$$u_1(\eta_1) = \begin{cases} \lambda - f_1 + m_L + q(m_H - m_L) + x^{(2)} + 2\epsilon\eta_1 - \frac{b}{2}(1+\eta_1)^2 \\ +\frac{(1-q)(m_H-m_L)}{r+1}(1+\eta_1)^{r+1} & \text{if } \eta_1 \le 0; \\ \lambda - f_1 + m_L + q(m_H - m_L) + x^{(2)} + 2\epsilon\eta_1 - \frac{b}{2}\left(1-\eta_1^2\right) \\ +\frac{(1-q)(m_H-m_L)}{r+1}\left(1-\eta_1^{r+1}\right) - \{b - (1-q)(m_H - m_L)\}\eta_1 & \text{if } \eta_1 > 0. \end{cases} \tag{15}$$

Then from (14) we get $u_1(x_1) = u_1(\eta_1)$ and $\frac{du_1}{dx_1} = \frac{1}{2\epsilon}\frac{du_1(\eta_1)}{d\eta_1}$ for $x^{(2)} - 2\epsilon \le x_1 \le x^{(2)} + 2\epsilon$ (corresponding to $-1 \le \eta_1 \le 1$). We calculate the first, second, and third derivatives of $u_1(\eta_1)$ as follows:

$$\frac{du_1(\eta_1)}{d\eta_1} = \begin{cases} 2\epsilon - b(1+\eta_1) + (1-q)(m_H - m_L)(1+\eta_1)^r & \text{if } \eta_1 \le 0; \\ 2\epsilon - b(1-\eta_1) + (1-q)(m_H - m_L)\left(1-\eta_1^r\right) & \text{if } \eta_1 > 0; \end{cases} \tag{16}$$

$$\frac{d^2u_1(\eta_1)}{d\eta_1^2} = \begin{cases} -b + r(1-q)(m_H - m_L)(1+\eta_1)^{r-1} & \text{if } \eta_1 \le 0; \\ b - r(1-q)(m_H - m_L)\eta_1^{r-1} & \text{if } \eta_1 > 0; \end{cases} \tag{17}$$

$$\frac{d^3u_1(\eta_1)}{d\eta_1^3} = \begin{cases} r(r-1)(1-q)(m_H - m_L)(1+\eta_1)^{r-2} & \text{if } \eta_1 \le 0; \\ -r(r-1)(1-q)(m_H - m_L)\eta_1^{r-2} & \text{if } \eta_1 > 0. \end{cases} \tag{18}$$

We next discuss three cases: (Case I) $r = 1$, (Case II) $r > 1$, and (Case III) $r < 1$.

(Case I) From (16), $\frac{du_1(\eta_1)}{d\eta_1}$ is linear in η_1. In addition, $\frac{du_1(-1)}{d\eta_1} = \frac{du_1(1)}{d\eta_1} = 2\epsilon > 0$ and $\frac{du_1(0)}{d\eta_1} = 2\epsilon - b + (1-q)(m_H - m_L)$. There are two cases regarding the sign of $\frac{du_1(0)}{d\eta_1}$. First, if $\epsilon \ge \frac{b-(1-q)(m_H-m_L)}{2}$ (which implies $2\epsilon - b + (1-q)(m_H - m_L) \ge 0$), then $\frac{du_1(\eta_1)}{d\eta_1} \ge 0$ for any $\eta_1 \in [-1, 1]$, and $\frac{du_1(x_1)}{dx_1} \ge 0$ in this case. Second, if $\epsilon < \frac{b-(m_H-m_L)}{2}$, then $\frac{du_1(0)}{d\eta_1} < 0$, and $\frac{du_1(\eta_1)}{d\eta_1}$ decreases from positive to negative, and then increases from negative to positive. In this case, $u_1(x_1)$ first increases with x_1, then decreases with x_1, and finally increases with x_1 again. The condition for the monotonic change of $u_1(x_1)$ is $\epsilon \ge \frac{b-(1-q)(m_H-m_L)}{2}$.

(Case II) We need to compare the minimum value of $\frac{du_1(\eta_1)}{d\eta_1}$ with 0 to determine the shape of $u_1(x_1)$. From (18), $\frac{d^3u_1(\eta_1)}{d\eta_1^3} > 0$ for $\eta_1 \le 0$ and $\frac{d^3u_1(\eta_1)}{d\eta_1^3} < 0$ for $\eta_1 > 0$. So $\frac{du_1(\eta_1)}{d\eta_1}$ is convex in η_1 for $\eta_1 \le 0$ and concave in η_1 for $\eta_1 > 0$. We can show that there exists a minimum value of $\frac{du_1(\eta_1)}{d\eta_1}$ on $(-\infty, 0]$. To get this minimum value, we solve $\frac{d^2u_1^-(\eta_1)}{d\eta_1^2} = 0$ from (17) and get $\eta_1^{(1)} = \left\{\frac{b}{r(1-q)(m_H-m_L)}\right\}^{\frac{1}{r-1}} - 1$.

If $\eta_1^{(1)} \le 0$ (which happens when $\frac{b}{r(1-q)(m_H-m_L)} \le 1$), then $\frac{du_1(\eta_1)}{d\eta_1}$ achieves its minimum value $\frac{du_1\left(\eta_1^{(1)}\right)}{d\eta_1} = 2\epsilon - \left\{\frac{b}{r(1-q)(m_H-m_L)}\right\}^{\frac{1}{r-1}} b\left(1 - \frac{1}{r}\right)$. If $\epsilon \ge \frac{1}{2}\left\{\frac{b}{r(1-q)(m_H-m_L)}\right\}^{\frac{1}{r-1}} b\left(1-\frac{1}{r}\right)$ (which implies $\frac{du_1\left(\eta_1^{(1)}\right)}{d\eta_1} \ge 0$), then $\frac{du_1(\eta_1)}{d\eta_1} \ge 0$ for any $\eta_1 \in [-1, 1]$ and $u_1(x_1)$ increases with x_1. If $\epsilon < \frac{1}{2}\left\{\frac{b}{r(1-q)(m_H-m_L)}\right\}^{\frac{1}{r-1}} b\left(1-\frac{1}{r}\right)$ (which implies $\frac{du_1\left(\eta_1^{(1)}\right)}{d\eta_1} < 0$), we can show that $\frac{du_1(\eta_1)}{d\eta_1}$ changes from positive to negative, and then from negative to positive for $\eta_1 \in [-1, 1]$ using $\frac{du_1(-1)}{d\eta_1} = \frac{du_1(1)}{d\eta_1} =$

$2\epsilon > 0$ and the fact that $\frac{du_1(\eta_1)}{d\eta_1}$ is convex in η_1 for $\eta_1 \le 0$ and concave in η_1 for $\eta_1 > 0$. In this case, $u_1(x_1)$ first increases with x_1, then decreases with x_1, and finally increases with x_1 again.

If $\eta_1^{(1)} > 0$ (which happens when $\frac{b}{r(1-q)(m_H-m_L)} > 1$), then $\frac{du_1(\eta_1)}{d\eta_1}$ achieves its minimum value $\frac{du_1(0)}{d\eta_1} = 2\epsilon - b + (1-q)(m_H - m_L)$. So we get the condition for $\frac{du_1(\eta_1)}{d\eta_1} \ge 0$ is $\epsilon \ge \frac{b-(1-q)(m_H-m_L)}{2}$. The rest of the proof is similar to case in which $\eta_1^{(1)} \le 0$.

(Case III) Similar to (Case II), we get the conditions for the monotonic change of $u_1(x_1)$ as follows: $\frac{b}{r(1-q)(m_H-m_L)} \ge 1$ and $\epsilon \ge \frac{b-(1-q)(m_H-m_L)}{2} - \frac{1}{2}\left\{\frac{b}{r(1-q)(m_H-m_L)}\right\}^{\frac{1}{r-1}} b\left(1-\frac{1}{r}\right)$, or $\frac{b}{r(1-q)(m_H-m_L)} < 1$ and $\epsilon \ge \frac{b-(1-q)(m_H-m_L)}{2}$.

Finally, by combining all the conditions in (Case I), (Case II), and (Case III), we can prove that if $b \le b^{(1)}$, $u_1(x_1)$ increases with x_1. □

Lemma O4 *(a) If $r \ge 1$, then there exists $x^{(b)} > x^{(2)} - 2\epsilon$ such that the following holds: $b_x^* < b^{(2)}$ if $x_{aggr}^{(1)} < x^{(b)}$. If $0 < r < 1$, then there exists $x^{(b)} < x^{(2)} + 2\epsilon$ such that the following holds: $b_x^* < b^{(2)}$ if $x_{aggr}^{(1)} > x^{(b)}$.*
(b) If $r > 1$, then there exists $x^{(\epsilon)} > x^{(2)} - 2\epsilon$ such that the following holds: $b_x^{**} < b^{(2)}$ if $x_{aggr}^{(1)} < x^{(\epsilon)}$. If $0 < r < 1$, then there exists $x^{(\epsilon)} < x^{(2)} + 2\epsilon$ such that the following holds: $b_x^{**} < b^{(2)}$ if $x_{aggr}^{(1)} > x^{(b)}$. If $r = 1$, then $b_x^{**} < b^{(2)}$.

Proof. **(a)** We will first prove the case of $r \ge 1$. Note that from the proof of Proposition 3 $b_x^* = (m_H - m_L)\left(1+\eta_{aggr}\right)^{r-1}\left\{\frac{2\epsilon(1+\eta_{aggr})}{f_H-m_L} - \frac{2\epsilon(r+1)(1+\eta_{aggr})}{f_H-m_L}\ln\left(1+\eta_{aggr}\right) + 1 - q\right\}$ for $-1 \le \eta_{aggr} \le 0$, where $\eta_{aggr} = \frac{x_{aggr}^{(1)} - x^{(2)}}{2\epsilon}$. As $x_{aggr}^{(1)} \to x^{(2)} - 2\epsilon$, $\eta_{aggr} \to -1$ and $b_x^* \to 0$, which is smaller than $b^{(2)}$. By continuity, for the given value $b^{(2)}$, there exists $x^{(b)} > x^{(2)} - 2\epsilon$ such that $b_x^* < b^{(2)}$ if $x_{aggr}^{(1)} \in [x^{(2)} - 2\epsilon, x^{(b)})$. In addition, if $x_{aggr}^{(1)} < x^{(2)} - 2\epsilon$, in the proof of Proposition 3 we have shown that $x_{aggr}^{(1)}$ does not change with r and $b_x^* = 0$. Combining all these conditions we can prove the case of $r \ge 1$.

We next prove the case of $0 < r < 1$. Note that from the proof of Proposition 3 $b_x^* = \frac{m_H-m_L}{1-\eta_{aggr}}\left\{\frac{2\epsilon\left(1-\eta_{aggr}^{r+1}\right)}{f_H-m_L} + \frac{2\epsilon(r+1)\eta_{aggr}^{r+1}}{f_H-m_L}\ln\eta_{aggr} + (1-q)\left(1-\eta_{aggr}^r\right)\right\}$ for $0 \le \eta_{aggr} \le 1$. Using L'Hospital's Rule we get $\lim_{\eta_{aggr}\to 1} b_x^* = r(1-q)(m_H - m_L)$. Similar to the case of $r \ge 1$, we need to prove $\lim_{\eta_{aggr}\to 1} b_x^* = r(1-q)(m_H - m_L) < b^{(2)}$. From (7), if $\min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\} \le r \le 1$, $b^{(2)} = 2\epsilon + (1-q)(f_H - m_L)$, which is larger than $\lim_{\eta_{aggr}\to 1} b_x^* = r(1-q)(m_H - m_L)$ because $f_H > m_H$ and $r < 1$. If $r < \min\left\{1, \frac{b}{(1-q)(f_H-m_L)}\right\}$, from (7) $b^{(2)}$ is the maximum solution of $g(x) = \frac{1-r}{\{(1-q)(f_H-m_L)\}^{\frac{1}{r-1}}}\left(\frac{x}{r}\right)^{\frac{r}{r-1}} + x - 2\epsilon - (1-q)(f_H - m_L) = 0$. To show $r(1-q)(m_H - m_L) < b^{(2)}$, we need to prove the following statements: $g(x)$ achieves its minimum value -2ϵ at $x = r(1-q)(f_H - m_L)$, and it is increasing with x if and only if $x > r(1-q)(f_H - m_L)$. From these two statements, $b^{(2)}$ must be on the right side of $r(1-q)(f_H - m_L)$ because $b^{(2)}$ is the maximum solution of $g(x) = 0$ and $g(x) > 0$ for sufficiently large x. So $b^{(2)} > r(1-q)(f_H - m_L) > r(1-q)(m_H - m_L)$. To prove the statements, we calculate $\frac{dg(x)}{dx} = 1 - \left\{\frac{x}{r(1-q)(f_H - m_L)}\right\}^{\frac{1}{r-1}}$, which has a root at $x = r(1-q)(f_H - m_L)$. Note that $\frac{1}{r-1} < 0$ because $r < 1$. We can show $\frac{dg(x)}{dx} > 0$ if and only if $x > r(1-q)(f_H - m_L)$. The function $g(x)$ achieves its minimum value $g(r(1-q)(f_H - m_L)) = -2\epsilon < 0$.

(b) The proofs for the cases of $r > 1$ and $0 < r < 1$ are similar to part (a). We focus on the case of $r = 1$. From the proof of Proposition 3, $b_x^{**} = (1-q)(m_H - m_L)$ if $r = 1$. From (7) $b^{(2)} = 2\epsilon + (1-q)(f_H - m_L)$ if $r = 1$. Since $f_H > m_H$, we can prove that $b_x^{**} < b^{(2)}$. □

Proof of Lemma 2. (a) Following the same procedure as in the proof of Lemma 1, we show that if all firms but firm i follow a switching strategy around $\widehat{x}^{(2)}$, then firm i's best response is to follow this switching strategy as well. Similar to Lemma 1, we first derive the expected gain $\widehat{u}_i(x_i)$ when other firms follow a switching strategy around $\widehat{x}^{(2)}$. We can show that if $b \leq 2\epsilon$, then $\widehat{u}_i\left(\widehat{x}^{(2)}\right) = 0$, and $\widehat{u}_i(x_i)$ is nondecreasing with x_i. Thus $\widehat{u}_i(x_i) > 0$ if and only if $x_i > \widehat{x}^{(2)}$.

(b) Following the same procedure as in the proof of Lemma 1, we obtain the expression of $\widehat{u}_1(x_1)$ as follows:

$$\widehat{u}_1(x_1) = \begin{cases} \lambda - f_1 + m_L + \widehat{q}(m_H - m_L) + x_1 & \text{if } x_1 < \widehat{x}^{(2)} - 2\epsilon; \\ \lambda - f_1 + m_L + \widehat{q}(m_H - m_L) + x_1 - \frac{b}{2}\left(\frac{x_1 - \widehat{x}^{(2)} + 2\epsilon}{2\epsilon}\right)^2 & \text{if } \widehat{x}^{(2)} - 2\epsilon \leq x_1 < \widehat{x}^{(2)}; \\ \lambda - f_1 + m_L + \widehat{q}(m_H - m_L) + x_1 & \\ \quad -\frac{b}{2}\left\{1 - \left(\frac{x_1 - \widehat{x}^{(2)}}{2\epsilon}\right)^2\right\} - b\left(\frac{x_1 - \widehat{x}^{(2)}}{2\epsilon}\right) & \text{if } \widehat{x}^{(2)} \leq x_1 \leq \widehat{x}^{(2)} + 2\epsilon; \\ \lambda - f_1 + m_L + \widehat{q}(m_H - m_L) + x_1 - b & \text{if } x_1 > \widehat{x}^{(2)} + 2\epsilon. \end{cases} \tag{19}$$

The rest of the proof follows the same procedure as in the proof of Proposition 1. □

Proof of Proposition 4. We first solve for the value of r that results in $x^{(2)} = \widehat{x}^{(2)}$. Noting that $x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}(1-q)(f_H - m_L)$ from Lemma 1 and $\widehat{x}^{(2)} = \frac{1}{2}b + f_L - (1-\widehat{q})m_L - \widehat{q}f_H$ from Lemma 2(a), we solve $x^{(2)} = \widehat{x}^{(2)}$ and obtain $r = \frac{1-q}{\widehat{q}-q} - 1$. From the condition $r > 0$, we obtain $\frac{1-q}{\widehat{q}-q} > 0$ and $\widehat{q} > q$.

To compare $x_{aggr}^{(1)}$ and $\widehat{x}^{(1)}$, we compare $u_1(x_1)$ in (14) and $\widehat{u}_1(x_1)$ in (19) for $x_1 = \widehat{x}^{(1)}$ given that $r = \frac{1-q}{\widehat{q}-q} - 1$. If $u_1(\widehat{x}^{(1)}) \geq \widehat{u}_1(\widehat{x}^{(1)}) = 0$, then $x_{aggr}^{(1)} \leq \widehat{x}^{(1)}$ because $u_1(x_1) \geq 0$ for $x_1 \geq x_{aggr}^{(1)}$. To compare $u_1(\widehat{x}^{(1)})$ and $\widehat{u}_1(\widehat{x}^{(1)})$, we compute $u_1(\widehat{x}^{(1)}) - \widehat{u}_1(\widehat{x}^{(1)})$ using (19) and the expression of

$u_1(x_1)$ in the proof of Proposition 3:

$$u_1(\widehat{x}^{(1)})-\widehat{u}_1(\widehat{x}^{(1)}) = \begin{cases} (q-\widehat{q})(m_H-m_L) & \text{if } \widehat{x}^{(1)} < \widehat{x}^{(2)} - 2\epsilon; \\ (\widehat{q}-q)(m_H-m_L)\left\{\left(1+\frac{\widehat{x}^{(1)}-\widehat{x}^{(2)}}{2\epsilon}\right)^{r+1}-1\right\} & \text{if } \widehat{x}^{(2)} - 2\epsilon \le \widehat{x}^{(1)} < \widehat{x}^{(2)}; \\ (m_H-m_L)\left(\frac{\widehat{x}^{(1)}-\widehat{x}^{(2)}}{2\epsilon}\right)\left\{1-q-(\widehat{q}-q)\left(\frac{\widehat{x}^{(1)}-\widehat{x}^{(2)}}{2\epsilon}\right)^{r}\right\} & \text{if } \widehat{x}^{(2)} \le \widehat{x}^{(1)} \le \widehat{x}^{(2)} + 2\epsilon; \\ (1-\widehat{q})(m_H-m_L) & \text{if } \widehat{x}^{(1)} > \widehat{x}^{(2)} + 2\epsilon. \end{cases} \tag{20}$$

From (20) $u_1(\widehat{x}^{(1)}) - \widehat{u}_1(\widehat{x}^{(1)}) = 0$ if $m_H = m_L$. In this case $x^{(1)}_{aggr} = \widehat{x}^{(1)}$. We next examine the case in which $m_H > m_L$. From (20) $u_1(\widehat{x}^{(1)}) - \widehat{u}_1(\widehat{x}^{(1)}) < 0$ if $\widehat{x}^{(1)} < \widehat{x}^{(2)} - 2\epsilon$, and $u_1(\widehat{x}^{(1)}) - \widehat{u}_1(\widehat{x}^{(1)}) > 0$ if $\widehat{x}^{(1)} > \widehat{x}^{(2)} + 2\epsilon$ (note that we have shown $\widehat{q} > q$). We next show that $d\left\{u_1\left(\widehat{x}^{(1)}\right) - \widehat{u}_1\left(\widehat{x}^{(1)}\right)\right\}/d\widehat{x}^{(1)} \ge 0$ such that there exists $x^{(q)}$ such that $u_1(\widehat{x}^{(1)}) - \widehat{u}_1(\widehat{x}^{(1)}) \ge 0$ if and only if $\widehat{x}^{(1)} \ge x^{(q)}$. From (20) we get the following:

$$\frac{d\left\{u_1\left(\widehat{x}^{(1)}\right)-\widehat{u}_1\left(\widehat{x}^{(1)}\right)\right\}}{d\widehat{x}^{(1)}} = \begin{cases} 0 & \text{if } \widehat{x}^{(1)} < \widehat{x}^{(2)} - 2\epsilon; \\ \frac{(1-q)(m_H-m_L)}{2\epsilon}\left(1+\frac{\widehat{x}^{(1)}-\widehat{x}^{(2)}}{2\epsilon}\right)^{r} & \text{if } \widehat{x}^{(2)} - 2\epsilon \le \widehat{x}^{(1)} < \widehat{x}^{(2)}; \\ \frac{(1-q)(m_H-m_L)}{2\epsilon}\left\{1-\left(\frac{\widehat{x}^{(1)}-\widehat{x}^{(2)}}{2\epsilon}\right)^{r}\right\} & \text{if } \widehat{x}^{(2)} \le \widehat{x}^{(1)} \le \widehat{x}^{(2)} + 2\epsilon; \\ 0 & \text{if } \widehat{x}^{(1)} > \widehat{x}^{(2)} + 2\epsilon. \end{cases}$$

We can verify $d\left\{u_1\left(\widehat{x}^{(1)}\right) - \widehat{u}_1\left(\widehat{x}^{(1)}\right)\right\}/d\widehat{x}^{(1)} \ge 0$ for any $\widehat{x}^{(1)}$ because $r > 0$.

We finally change the condition $\widehat{x}^{(1)} \ge x^{(q)}$ to a condition on λ using the implicit function theorem. Note that $\widehat{x}^{(1)}$ is the solution of $\widehat{u}_1(x_1) = 0$ and $\widehat{u}_1(x_1)$ increases linearly with λ from (19). By the implicit function theorem, $\frac{d\widehat{x}_1}{d\lambda} = -\left.\frac{\partial \widehat{u}_1/\partial\lambda}{\partial\widehat{u}_1/\partial x_1}\right|_{x_1=\widehat{x}^{(1)}} < 0$ because $\widehat{u}_1(x_1)$ increases with x_1 at $x_1 = \widehat{x}^{(1)}$. So there exists $\widehat{\lambda}$ such that $\widehat{x}^{(1)} \ge x^{(q)}$ if and only if $\lambda \le \widehat{\lambda}$. $\square$

Proposition O1 *(a) Under the regulation that considers industry capability, the following results hold: The threshold $x^{(2)}$ is decreasing with q. If $x^{(1)}_{aggr} < x^{(2)} - 2\epsilon$, then $x^{(1)}_{aggr}$ is decreasing with q. If $x^{(2)} - 2\epsilon \le x^{(1)}_{aggr} \le x^{(2)} + 2\epsilon$, then there exists a threshold b^{***}_x such that $x^{(1)}_{aggr}$ is decreasing with q if and only if $b < b^{***}_x$. If $x^{(1)}_{aggr} > x^{(2)} + 2\epsilon$, then $x^{(1)}_{aggr}$ is independent of q.*
(b) Under the regulation that does not consider industry capability, the following results hold: The threshold $\widehat{x}^{(2)}$ is decreasing with $\widehat{q}$. If $\widehat{x}^{(1)} < \widehat{x}^{(2)} - 2\epsilon$ or $\widehat{x}^{(1)} > \widehat{x}^{(2)} + 2\epsilon$, then $\widehat{x}^{(1)}$ is decreasing with $\widehat{q}$. If $\widehat{x}^{(2)} - 2\epsilon \le \widehat{x}^{(1)} \le \widehat{x}^{(2)} + 2\epsilon$, then there exists a threshold $\widehat{b}^{***}_x$ such that $\widehat{x}^{(1)}$ is decreasing with $\widehat{q}$ if and only if $b < \widehat{b}^{***}_x$.

Proof. (a) The result that the threshold $x^{(2)}$ is decreasing with q follows directly from $x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}(1-q)(f_H - m_L)$ in Lemma 1 and $f_H > m_L$.

As in the proof of Proposition 3(b), we can show that $\frac{dx^{(1)}_{aggr}}{dq}$ has the same sign as $-\left.\frac{\partial u_1}{\partial q}\right|_{x_1=x^{(1)}_{aggr}}$. We examine the sign of $\left.\frac{\partial u_1}{\partial q}\right|_{x_1=x^{(1)}_{aggr}}$ in the following four cases: (Case I) $x^{(1)}_{aggr} < x^{(2)} - 2\epsilon$, (Case

II) $x^{(2)} - 2\epsilon \le x_{aggr}^{(1)} \le x^{(2)}$, (Case III) $x^{(2)} < x_{aggr}^{(1)} \le x^{(2)} + 2\epsilon$, and (Case IV) $x_{aggr}^{(1)} > x^{(2)} + 2\epsilon$.
(Cases I) From (14) we obtain $\frac{\partial u_1}{\partial q} = m_H - m_L > 0$. So $x_{aggr}^{(1)}$ is decreasing with q.
(Case II) Note that $\frac{du_1}{dq} = \frac{\partial u_1}{\partial q} + \frac{\partial u_1}{\partial \eta_1}\frac{d\eta_1}{dx^{(2)}}\frac{dx^{(2)}}{dq}$, where $\frac{d\eta_1}{dx^{(2)}} = -\frac{1}{2\epsilon}$ and $\frac{dx^{(2)}}{dq} = -\frac{r}{r+1}\left(f_H - m_L\right)$ from Lemma 1. Using this expression and (14), we obtain the following:

$$\frac{du_1}{dq} = \left(m_H - m_L\right)\left\{1 - \frac{\left(1+\eta_1\right)^{r+1}}{r+1}\right\} + \left\{\left(1-q\right)\left(m_H - m_L\right)\left(1+\eta_1\right)^r - b\left(1+\eta_1\right)\right\}\frac{r\left(f_H - m_L\right)}{2\epsilon\left(r+1\right)}.$$

Let $b_x^{***} = \frac{m_H - m_L}{1+\eta_{aggr}}[\frac{2\epsilon(r+1)}{r(f_H - m_L)}\{1 - \frac{\left(1+\eta_{aggr}\right)^{r+1}}{r+1}\} + (1-q)\left(1+\eta_{aggr}\right)^r]$, where $\eta_{aggr} = \frac{x_{aggr}^{(1)} - x^{(2)}}{2\epsilon}$. We can show $b_x^{***} \ge 0$ for $-1 \le \eta_{aggr} \le 0$. Then from the above equation, we get $\frac{du_1}{dq} > 0$ and thus $\frac{dx_{aggr}^{(1)}}{dq} < 0$ if and only if $b < b_x^{***}$.
(Case III) Similar to Case II, we obtain

$$\frac{du_1}{dq} = \left(m_H - m_L\right)\left(1 - \eta_1 - \frac{1-\eta_1^{r+1}}{r+1}\right) + \left\{\left(1-q\right)\left(m_H - m_L\right)\left(1-\eta_1^r\right) - b\left(1-\eta_1\right)\right\}\frac{r\left(f_H - m_L\right)}{2\epsilon\left(r+1\right)}.$$

Let $b_x^{***} = \frac{m_H - m_L}{1-\eta_1}\{\frac{2\epsilon(r+1)}{r(f_H - m_L)}(1 - \eta_{aggr} - \frac{1-\eta_{aggr}^{r+1}}{r+1}) + (1-q)\left(1-\eta_{aggr}^r\right)\}$. We can show $b_x^{***} \ge 0$ for $0 \le \eta_{aggr} \le 1$. Then we get $\frac{du_1}{dq} > 0$ and thus $\frac{dx_{aggr}^{(1)}}{dq} < 0$ if and only if $b < b_x^{***}$.
(Case IV) From (14) we obtain $\frac{du_1}{dq} = 0$. So $x_{aggr}^{(1)}$ is independent of q.
(b) The result that the threshold $\widehat{x}^{(2)}$ is decreasing with $\widehat{q}$ follows directly from $\widehat{x}^{(2)} = \frac{1}{2}b + f_L - (1-\widehat{q})\,m_L - \widehat{q}f_H$ in Lemma 2 and $f_H > m_L$.

Similar to (a), we can show that $\frac{d\widehat{x}^{(1)}}{d\widehat{q}}$ has the same sign as $-\left.\frac{\partial\widehat{u}_1}{\partial\widehat{q}}\right|_{x_1=\widehat{x}^{(1)}}$. We examine the sign of $\left.\frac{\partial\widehat{u}_1}{\partial\widehat{q}}\right|_{x_1=\widehat{x}^{(1)}}$ in the following four cases: (Case I) $\widehat{x}^{(1)} < \widehat{x}^{(2)} - 2\epsilon$, (Case II) $\widehat{x}^{(2)} - 2\epsilon \le \widehat{x}^{(1)} \le \widehat{x}^{(2)}$, (Case III) $\widehat{x}^{(2)} < \widehat{x}^{(1)} \le \widehat{x}^{(2)} + 2\epsilon$, and (Case IV) $\widehat{x}^{(1)} > \widehat{x}^{(2)} + 2\epsilon$.
(Cases I and IV) From (14) we obtain $\frac{\partial\widehat{u}_1}{\partial\widehat{q}} = m_H - m_L > 0$. So $\widehat{x}^{(1)}$ is decreasing with $\widehat{q}$.
(Case II) From (14) and $\widehat{x}^{(2)} = \frac{1}{2}b + f_L - (1-\widehat{q})\,m_L - \widehat{q}f_H$ in Lemma 2 we obtain

$$\frac{d\widehat{u}_1}{d\widehat{q}} = \left(m_H - m_L\right) - \frac{b\left(f_H - m_L\right)}{2\epsilon}\left(\frac{\widehat{x}^{(1)} - \widehat{x}^{(2)} + 2\epsilon}{2\epsilon}\right).$$

Let $\widehat{b}_x^{***} = \frac{4\epsilon^2(m_H - m_L)}{(f_H - m_L)\left(\widehat{x}^{(1)} - \widehat{x}^{(2)} + 2\epsilon\right)}$. From the above equation, we get $\frac{d\widehat{u}_1}{d\widehat{q}} > 0$ and thus $\frac{d\widehat{x}^{(1)}}{d\widehat{q}} < 0$ if and only if $b < \widehat{b}_x^{***}$.
(Case III) Similar to Case II, we obtain

$$\frac{d\widehat{u}_1}{d\widehat{q}} = \left(m_H - m_L\right) - \frac{b\left(f_H - m_L\right)\left\{2\epsilon - \left(\widehat{x}^{(1)} - \widehat{x}^{(2)}\right)\right\}}{4\epsilon^2}.$$

Let $\widehat{b}_x^{***} = \frac{4\epsilon^2(m_H - m_L)}{(f_H - m_L)(2\epsilon - \widehat{x}^{(1)} + \widehat{x}^{(2)})}$. Then $\frac{d\widehat{u}_1}{d\widehat{q}} > 0$ and thus $\frac{d\widehat{x}^{(1)}}{d\widehat{q}} < 0$ if and only if $b < \widehat{b}_x^{***}$. $\square$

B Additional Analysis on the Existence of Equilibrium

We have shown that an equilibrium in period 2 exists if b is sufficiently small. We have also provided a sufficient condition in Lemma 1 for the existence of an equilibrium: $b \leq b^{(2)}$. In Proposition 3(b), we have shown that $x_{aggr}^{(1)}$ is nonincreasing with r if and only if $b > b_x^*$; i.e., this result requires b to be sufficiently large. These two conditions (an equilibrium in period 2 exists and $b > b_x^*$) pose constraints on b on different directions. We have analytically proven in Lemma O4 that there always exists an interval of $x_{aggr}^{(1)}$ in which $b_x^* < b^{(2)}$ and these two conditions can hold simultaneously. In this section, we numerically analyze the regions in which both constraints are satisfied. We find that these regions comprise significant portions of the parameter space in which $x_{aggr}^{(1)}$ is dependent on r. We also obtain similar results for the regions in which $b > b_x^{**}$ and an equilibrium exists.

We perform our numerical experiment as follows. Notice that in Lemma O4 we have shown that there always exists an interval of $x_{aggr}^{(1)}$ in which $b_x^* < b^{(2)}$. So we use $x_{aggr}^{(1)}$ as the x-axis and b as the y-axis to show the region in which $b > b_x^*$ and an equilibrium exists. Since the equilibrium is more likely to exist when the complementarity effect is strong, we normalize the x-axis and y-axis with respect to $(f_H - m_L)$, which is the coefficient of α^r in firm i's utility function in equation (1) and affects the complementarity effect. Since the existence of an equilibrium is strongly affected by the magnitude of uncertainty, we plot figures with two uncertainty values: $\epsilon = 0.1\,(f_H - m_L)$ (small uncertainty) and $\epsilon = 0.3\,(f_H - m_L)$ (moderate uncertainty). We also plot figures with two values of r to reflect the strength of regulation: $r = 0.3$ (strong regulation) and $r = 3$ (moderate regulation). Finally, since the coefficient of α^r in firm i's utility function in equation (1) is $(f_H - m_L)$ and the coefficient in firm 1's utility function in equation (2) is $(m_H - m_L)$, we check the following values of $(m_H - m_L)$: $m_H - m_L = (f_H - m_L)/4$, $m_H - m_L = (f_H - m_L)/2$ and $m_H - m_L = f_H - m_L$. We do not include different values of λ and f_1 because $x_{aggr}^{(1)}$ decreases with $(\lambda - f_1)$; different values of $x_{aggr}^{(1)}$ on the x-axis already cover possible values of λ and f_1. We focus on the case in which $q = 0$ because the cases with $q > 0$ are just rescales of the axis without changing the shape of different regions.

We plot Figure 4 with $m_H - m_L = (f_H - m_L)/4$. Figures 4(a)-(d) correspond to different values of ϵ and r. The value $\bar{b}$ is a *numerically computed* upper bound on b that guarantees the existence of an equilibrium. The value $b^{(2)}$ is the bound specified by the sufficient condition in Lemma 1. Besides $\bar{b}$ and $b^{(2)}$, two lines and one curve separate a figure into four regions. In the left and right regions $x_{aggr}^{(1)}$ is independent of r because in these regions firm 1 expects $\alpha = 0$ or $\alpha = 1$

and α is not affected by r. In the lower region, $x^{(1)}_{aggr}$ is strictly increasing with r, and in the upper region $x^{(1)}_{aggr}$ is strictly decreasing with r. The curve that separates the upper region and the lower region is b^*_x. We can see that in all figures the upper region, in which $x^{(1)}_{aggr}$ is strictly increasing with r, takes more than half of the middle region, in which $x^{(1)}_{aggr}$ is dependent on r.

Figure 5 corresponds to $m_H - m_L = (f_H - m_L)/2$, indicating the complementarity effect for firm 1 is larger than that in Figure 4. As a result, larger values of b are required to observe that $x^{(1)}_{aggr}$ is decreasing with r because this result happens when the substitutability effect dominates the complementarity effect, yielding smaller regions in which $x^{(1)}_{aggr}$ is strictly increasing with r than Figure 4. Nevertheless, the upper region still takes about one third of the figure's middle region.

Figure 6 corresponds to the maximum possible value of $(m_H - m_L)$: $m_H - m_L = f_H - m_L$ (note that $f_H \geq 0$ and $m_H \leq 0$). Figure 6 shows that even in this extreme case, an upper region in a figure still takes a considerable portion of the figure's middle region.

To sum up, Figures 4, 5, and 6 show that the region in which $b > b^*_x$ and an equilibrium exists (such that $x^{(1)}_{aggr}$ is decreasing with r) takes a significant portion of the region in which an equilibrium exists and $x^{(1)}_{aggr}$ is affected by r. So our result that $x^{(1)}_{aggr}$ is decreasing with r when b is sufficiently large is quite robust.

Similarly, Figures 7, 8, and 9 show the region in which $b > b^{**}_x$ and an equilibrium exists (such that $x^{(1)}_{aggr}$ is decreasing with ϵ if $x^{(1)}_{aggr} > x^{(2)}$, and increasing with ϵ if $x^{(1)}_{aggr} < x^{(2)}$) also takes a significant portion of the region in which an equilibrium exists and $x^{(1)}_{aggr}$ is affected by ϵ. Our result that uncertainty may encourage innovation when b is sufficiently large is also quite robust.

C Extension: Discovery of a New Technology by a Non-Leading Firm

In the base model, if the leading firm does not develop the technology, then there will be no technology available to reduce the pollutant. In this section we study the following case: If the leading firm does not develop the technology, then there is a probability $q_d < 1$ that another firm will discover and implement a similar technology.

We solve this problem backward. First, we analyze firm 1's decision if the technology has been discovered by another firm. In this case, the leading firm is similar to a following firm in the base model. Following the same procedure as in §4.1.2 of the main body, we obtain firm 1's decision as follows: adopt the technology if $x_1 \geq x^{(2)}$, where $x^{(2)} = \frac{b}{2} + f_L - f_H + \frac{r}{r+1}(1-q)(f_H - m_L)$ is the same as that in Lemma 1.

Next, we study firm 1's decision in the first period. If firm 1 decides to develop the technology, then its expected payoff for any given θ and α is $\pi^{(1)}_1(1;\theta,\alpha) = \lambda - f_1 + \pi^{(2)}_1(\theta,\alpha)$, where $\pi^{(2)}_1(\theta,\alpha)$

is the payoff received after period 1 with the following expression:

$$\pi_1^{(2)}(\theta,\alpha) = m_L + q(m_H - m_L) + \theta - b\alpha + \alpha^r(1-q)(m_H - m_L).$$

Here we use the superscript "(1)" to denote the first period, and "(2)" to denote the time after period 1. If firm 1 decides not to develop the technology, in the base model the expected payoff is zero. However, in this case there is a probability q_d that another firm will discover the technology. If $x_1 \geq x^{(2)}$, then firm 1 will adopt the technology after the discovery of the technology, and its expected payoff from adopting the technology is $\pi_1^{(1)}\left(0;\theta,\alpha|x_1 \geq x^{(2)}\right) = -f_L + \pi_1^{(2)}(\theta,\alpha)$. If $x_1 < x^{(2)}$, then firm 1 will not adopt the technology after the discovery of the technology by the other firm, and its expected payoff from not adopting the technology is $\pi_1^{(1)}\left(0;\theta,\alpha|x_1 < x^{(2)}\right) = \{q + (1-q)\alpha^r\}(m_H - f_H)$. Using the expressions of $\pi_1^{(1)}(1;\theta,\alpha)$, $\pi_1^{(1)}\left(0;\theta,\alpha|x_1 \geq x^{(2)}\right)$, and $\pi_1^{(1)}\left(0;\theta,\alpha|x_1 < x^{(2)}\right)$, we obtain the expected gain of developing the technology in period 1:

$$\begin{aligned} u_1(\theta,\alpha) &\equiv \begin{cases} \pi_1^{(1)}(1;\theta,\alpha) - q_d\pi_1^{(1)}\left(0;\theta,\alpha|x_1 < x^{(2)}\right) & \text{if } x_1 < x^{(2)}; \\ \pi_1^{(1)}(1;\theta,\alpha) - q_d\pi_1^{(1)}\left(0;\theta,\alpha|x_1 \geq x^{(2)}\right) & \text{if } x_1 \geq x^{(2)}; \end{cases} \\ &= \begin{cases} \begin{array}{l} \lambda - f_1 + m_L + q\{(m_H - m_L) - q_d(m_H - f_H)\} + \theta - b\alpha + \\ \alpha^r(1-q)\{(m_H - m_L) - q_d(m_H - f_H)\} \end{array} & \text{if } x_1 < x^{(2)}; \\ \begin{array}{l} \lambda - f_1 + q_d f_L + (1-q_d) \\ \{m_L + q(m_H - m_L) + \theta - b\alpha + \alpha^r(1-q)(m_H - m_L)\} \end{array} & \text{if } x_1 \geq x^{(2)}. \end{cases} \end{aligned} \tag{21}$$

By comparing (21) with equation (2) of the main body (the expression of the expected gain in the base model), we can see that they have the same functional forms except some differences in the coefficients of θ, α, α^r, and constant terms.[19] As a result, although the specific values of thresholds now depend on the new parameter q_d, all the qualitative insights obtained in §4 and §5 continue to hold.

D Extension: Firm 1 May Not Implement the Technology

In the base model, if the leading firm develops the technology, it always implements the technology. In this section, we study the following case: If the leading firm develops the technology, then there is a probability $q_f < 1$ that the technology fails to meet expectations and the leading firm does not implement it.

If firm 1 develops the technology but it does not implement it, then it incurs a development

[19] The term $(\theta - b\alpha)$ in equation (2) of the main body remains the same if $x < x^{(2)}$, or changes to $(1-q_d)(\theta - b\alpha)$ if $x \geq x^{(2)}$. The term $\alpha^r(1-q)(m_H - m_L)$ in equation (2) of the main body changes to $\alpha^r(1-q)\{(m_H - m_L) - q_d(m_H - f_H)\}$ if $x < x^{(2)}$ or $(1-q_d)\alpha^r(1-q)(m_H - m_L)$ if $x \geq x^{(2)}$. These changes do not alter the signs of the coefficients.

cost f_1, while receiving zero benefits. If firm 1 develops the technology and implements it, then its expected gain is given in equation (2) in §3. Combining both cases, we obtain firm 1's expected gain for any given θ and α:

$$\begin{aligned} u_1(\theta,\alpha) &= (1-q_f)\{\lambda - f_1 + m_L + q(m_H - m_L) + \theta - b\alpha + \alpha^r(1-q)(m_H - m_L)\} - f_1 q_f \\ &= (1-q_f)\{\lambda + m_L + q(m_H - m_L) + \theta - b\alpha + \alpha^r(1-q)(m_H - m_L)\} - f_1. \end{aligned} \tag{22}$$

By comparing (22) with equation (2) in §3 (the expression of the expected gain in the base model), we can see that they have the same functional forms except that every term but f_1 is multiplied by $(1-q_f)$. As a result, although the specific values of thresholds now depend on the new parameter q_f, all the qualitative insights obtained in §4 and §5 continue to hold.

E Extension: Credits of Voluntary Adopters

In the base model, we use the condition $m_L \leq m_H$ to capture the positive benefit new regulation generates for a voluntary adopter by eliminating its cost disadvantage. In this extension, we focus on another potential benefit from early adoption: compliance credits accumulated before new regulation is enforced. For example, when the NHTSA announced a new corporate average fuel economy standard, Toyota gained a significant amount of fuel economy credits that could be used to reduce compliance to future standards, because Toyota's average fuel economy met the new standard long before the enforcement of the standard (NHTSA 2009).

The model is similar to the base model, except that the payoffs in period 3 are slightly different. As in the base model, the firms that have adopted the technology before period 3 receive m_L in period 3 if new regulation is not enforced, and receive m_H if new regulation is enforced. We assume $m_L \leq 0$ to reflect the fact that the green technology tends to be more expensive to use, and we use $m_H - m_L \geq 0$ to model the benefit of credits under new regulation. Those firms that have not adopted the technology before period 3 receive 0 in period 3 if new regulation is not enforced, and receive m_L if new regulation is enforced. Since they have not used the green technology before period 3, they cannot accumulate any credits. The two differences between this model and the base model are the following. First, in this model we do not restrict m_H to be nonnegative as in the base model, such that the benefit of accumulating credits is not constrained. Second, a firm that is forced to adopt the new technology in period 3 receives m_L in this model instead of m_H as in the base model. We make these two changes because in this model the early adopters receive benefits relative to those who are forced to adopt, in the form of accumulated credits. This benefit does not exist in the base model, where the benefit is the elimination of cost disadvantage.

Similar to the base model, for any given θ and α, if firm i ($\in [0,1)$) adopts the new green technology in period 2 (i.e., $a_i = 1$ in period 2), then its total expected payoff is given as $\pi_i(1;\theta,\alpha) \equiv -f_L + \theta - b\alpha + \{q + (1-q)\alpha^r\} m_H + \{1 - q - (1-q)\alpha^r\} m_L$; and if firm i chooses $a_i = 0$, its total expected payoff is $\pi_i(0;\theta,\alpha) \equiv \{q + (1-q)\alpha^r\}(m_L - f_H)$. Thus, the expected gain from adopting the technology, $u_i(\theta,\alpha)$, is

$$\begin{aligned} u_i(\theta,\alpha) &\equiv \pi_i(1;\theta,\alpha) - \pi_i(0;\theta,\alpha) \\ &= -f_L + m_L + q(f_H - 2m_L + m_H) + \theta - b\alpha + \alpha^r(1-q)(f_H - 2m_L + m_H). \end{aligned} \tag{23}$$

Similarly, the expected gain of firm 1 is

$$u_1(\theta,\alpha) = \lambda - f_1 + m_L + q(m_H - m_L) + \theta - b\alpha + \alpha^r(1-q)(m_H - m_L).$$

The above expression of $u_1(\theta,\alpha)$ is exactly the same as that in (2). The expression of $u_i(\theta,\alpha)$ in (23) is similar to that in (1), except that there is an additional positive term $(m_H - m_L)$ in the coefficient for α^r and in the coefficient for q. Therefore, except that the expression of $x^{(2)}$ and the specific values of thresholds will be slightly different from the base model, all the qualitative insights obtained in §4 and §5 continue to hold.

F Extension: Welfare Maximizing Government

In our base model, we use $q + (1-q)\alpha^r$ (where $r \in (0,\infty)$) to model regulation probability that is increasing with the voluntary adoption level. In this section we study a case in which the government agency maximizes social welfare. We show that if the government agency's regulation cost is a convex function of the number of firms, and if the regulation cost is the agency's private information, then from a firm's point of view the regulation probability is increasing with the voluntary adoption level. We further show that our insights from the main body hold through numerical studies. For notational convenience, we use subscript "wm" (welfare maximizing) to denote thresholds in this case.

The games in periods 1 and 2 are the same as in the base model. In period 3, the government agency decides whether to enforce a stricter new standard to maximize social welfare. We normalize social welfare in the absence of the new regulation to 0. If the agency enforces new regulation, social welfare consists of four parts. The first part is positive externality from pollution reduction. Denote by e the unit externality generated if one firm implements the new green technology. If the new regulation is enforced, $(1-\alpha)$ firms are forced to implement the technology. The total externality is $e(1-\alpha)$ (noting that firms are uniformly distributed on $[0,1)$ with unit density). The second part is the payoff of those firms that have not implemented the technology. A firm has to pay f_H to implement the technology, and it will receive m_H in period 3. The total payoff is $-(f_H - m_H)(1-\alpha)$. The third part is the payoff of those firms that have already implemented the technology. In the absence of the new regulation, each of these firms' payoff is m_L. With the new regulation, the payoff is m_H. So the total difference is $(m_H - m_L)\alpha$. The last part is the government agency's cost. The government agency receives a fine $(f_H - f_L)(1-\alpha)$ from those firms that have not implemented the technology. The government agency also incurs a regulation cost $f_r(1-\alpha)^k$, where $f_r > 0$ is the coefficient of the cost. We assume $k > 1$ such that the cost is a convex function of the number of firms that will be forced to implement the technology. The convex cost function indicates that it is increasingly more difficult to force firms to implement the green technology as the number of firms increases. Thus, the total welfare is

$$w(\alpha) = e(1-\alpha) - (f_H - m_H)(1-\alpha) + (m_H - m_L)\alpha + (f_H - f_L)(1-\alpha) - f_r(1-\alpha)^k. \quad (24)$$

The government agency enforces the new regulation if $w(\alpha) > 0$.

Since the regulation cost is usually not known to firms, we assume that firms have a belief that the cost coefficient is a random variable $\widetilde{f_r}$ with support on $(0,\infty)$. The probability of regulation is the probability of $w(\alpha) > 0$. Using (24) we obtain

$$\Pr(w(\alpha) > 0) = \Pr\left(\widetilde{f_r} < \{e - (f_L - m_L)\}(1-\alpha)^{1-k} + (m_H - m_L)(1-\alpha)^{-k}\right). \quad (25)$$

Since $\widetilde{f_r}$ is distributed on $(0,\infty)$, we assume $\{e-(f_L-m_L)\}(1-\alpha)^{1-k} + (m_H-m_L)(1-\alpha)^{-k} > 0$ such that $\Pr(w(\alpha) > 0)$ is positive; otherwise the problem is trivial. The condition $\{e-(f_L-m_L)\}$ $(1-\alpha)^{1-k} + (m_H-m_L)(1-\alpha)^{-k} > 0$ can be simplified to $e - (f_L - m_L) + \frac{m_H - m_L}{1-\alpha} > 0$. We next use this condition to show that $\{e-(f_L-m_L)\}(1-\alpha)^{1-k} + (m_H-m_L)(1-\alpha)^{-k}$ in (25) increases with α and k, and thus the probability of regulation $\Pr(w(\alpha) > 0)$ also increases with α and k. To do so, we differentiate $\{e-(f_L-m_L)\}(1-\alpha)^{1-k} + (m_H-m_L)(1-\alpha)^{-k}$ with respect to α and obtain the following:

$$
\begin{aligned}
& \frac{\partial}{\partial \alpha}\left[\left\{e-\left(f_L-m_L\right)\right\}(1-\alpha)^{1-k}+\left(m_H-m_L\right)(1-\alpha)^{-k}\right] \\
= \; & (1-\alpha)^{-k}\left[(k-1)\left\{e-\left(f_L-m_L\right)\right\}+k \frac{m_H-m_L}{1-\alpha}\right] \\
> \; & (1-\alpha)^{-k}\left[(k-1)\left\{e-\left(f_L-m_L\right)\right\}+(k-1) \frac{m_H-m_L}{1-\alpha}\right]>0,
\end{aligned}
$$

where the first inequality is due to $m_H - m_L > 0$ and $1-\alpha > 0$, and the last inequality is due to $e-(f_L-m_L)+\frac{m_H-m_L}{1-\alpha} > 0$. We differentiate $\{e-(f_L-m_L)\}(1-\alpha)^{1-k}+(m_H-m_L)(1-\alpha)^{-k}$ with respect to k and obtain the following:

$$
\begin{aligned}
& \frac{\partial}{\partial k}\left[\left\{e-\left(f_L-m_L\right)\right\}(1-\alpha)^{1-k}+\left(m_H-m_L\right)(1-\alpha)^{-k}\right] \\
= \; & -\ln(1-\alpha)\left[\left\{e-\left(f_L-m_L\right)\right\}(1-\alpha)^{1-k}+\left(m_H-m_L\right)(1-\alpha)^{-k}\right]>0,
\end{aligned}
$$

where the inequality is due to $\ln(1-\alpha) < 0$ and $\{e-(f_L-m_L)\}(1-\alpha)^{1-k}+(m_H-m_L)(1-\alpha)^{-k} > 0$. It is intuitive that the probability of regulation $\Pr(w(\alpha) > 0)$ increases with k: As k increases, the regulation cost $f_r(1-\alpha)^k$ decreases (noting that $1-\alpha < 1$). Define $\widehat{r} \equiv 1/k$, where $\widehat{r} \in (0,1)$ since $k > 1$. Then the regulation cost is $f_r(1-\alpha)^{\frac{1}{\widehat{r}}}$. The probability of regulation $\Pr(w(\alpha) > 0)$ decreases with $\widehat{r}$ and increases with α in a manner similar to our base model in which the regulation probability decreases with r and increases with α.

To sum up, if the regulation cost is a convex function $f_r(1-\alpha)^{\frac{1}{\widehat{r}}}$, where $f_r > 0$ and $0 < \widehat{r} < 1$, and f_r is private information to the government agency, then in a firm's belief the probability of regulation increases with the voluntary level α and decreases with $\widehat{r}$.

We next conduct a numerical study to show that our intuitions in the main body still hold in this case. Figure 11 shows that firm 1's expected gain from developing the technology is nonmonotonic with x_1: The function $u_1(x_1)$ can cross 0 three times and there are two intervals of x_1 in which $u_1(x_1) > 0$ ($\left[x_{wm}^{(1)}, y_{wm}^{(1)}\right]$ and $[z_{wm}^{(1)}, \infty)$), confirming our intuitions from Proposition 3(a) still hold in this case. Figure 12 shows how an increase of $\widehat{r}$ affects $x_{wm}^{(1)}$, the threshold of x_1 at which $u_1(x_1)$ crosses 0. When b is sufficiently large, Figure 12(a) shows that $x_{wm}^{(1)}$ decreases with $\widehat{r}$. When b is sufficiently small, Figure 12(b) shows that $x_{wm}^{(1)}$ increases with $\widehat{r}$. We can see that $\widehat{r}$ affects the threshold in the same direction as shown in Proposition 3(b). Figure 13 shows how an increase of ϵ affects the threshold $x_{wm}^{(1)}$. Figure 13(a) shows that larger uncertainty decreases $x_{wm}^{(1)}$ when b is sufficiently large, and Figure 13(b) shows that larger uncertainty increases $x_{wm}^{(1)}$ when b is sufficiently small (in both figures $x_{wm}^{(1)} > x_{wm}^{(2)}$). We can see that ϵ affects the threshold in the same direction as shown in Proposition 3(c).

G Extension: Information Advantage of the Leading Firm

In this section, we study a case in which firm 1's signal is more accurate than others; i.e., $\epsilon_1 \leq \epsilon$. Firm 1 will develop the new green technology if and only if the expected gain from this technology $u_1(x_1) \geq 0$. Since $u_1(x_1)$ depends on the voluntary adoption level α, we first derive the expression for α using Lemma 1. From Lemma 1, any other firm i ($\in [0,1)$) will adopt the technology when it observes its signal x_i ($= \theta + \widetilde{\varepsilon}_i$) higher than $x^{(2)}$. Thus, for any given θ, we can express α as follows:

$$\alpha = \begin{cases} 0 & \text{if } \theta < x^{(2)} - \epsilon; \\ \frac{\theta+\epsilon-x^{(2)}}{2\epsilon} & \text{if } x^{(2)} - \epsilon \leq \theta \leq x^{(2)} + \epsilon; \\ 1 & \text{if } \theta > x^{(2)} + \epsilon. \end{cases}$$

Since firm 1's signal is $x_1 = \theta + \widetilde{\varepsilon}_1$, where $\widetilde{\varepsilon}_1$ is uniformly distributed on $[-\epsilon_1, \epsilon_1]$, the posterior distribution of the fundamental θ is uniformly distributed on $[x_1 - \epsilon_1, x_1 + \epsilon_1]$ for any given x_1. Using this property, we can derive the following expression for $u_1(x_1)$:

$$u_1(x_1) = \begin{cases} \lambda - f_1 + m_L + q(m_H - m_L) + x_1, & \text{if } x_1 < x^{(2)} - \epsilon - \epsilon_1; \\ \begin{aligned} &\lambda - f_1 + m_L + q(m_H - m_L) + x_1 \\ &-\frac{\epsilon}{\epsilon_1}\frac{b}{2}\left(\frac{\epsilon_1+\epsilon}{2\epsilon} + \frac{x_1-x^{(2)}}{2\epsilon}\right)^2 \\ &+\frac{\epsilon}{\epsilon_1}\frac{(1-q)(m_H-m_L)}{r+1}\left(\frac{\epsilon_1+\epsilon}{2\epsilon} + \frac{x_1-x^{(2)}}{2\epsilon}\right)^{r+1}, \end{aligned} & \begin{aligned} &\text{if } x^{(2)} - \epsilon - \epsilon_1 \leq x_1 \\ &\leq x^{(2)} - \epsilon + \epsilon_1; \end{aligned} \\ \begin{aligned} &\lambda - f_1 + m_L + q(m_H - m_L) + x_1 + \frac{(1-q)(m_H-m_L)\epsilon}{(r+1)\epsilon_1} \cdot \\ &\left\{\left(\frac{x_1+\epsilon_1+\epsilon-x^{(2)}}{2\epsilon}\right)^{r+1} - \left(\frac{x_1-\epsilon_1+\epsilon-x^{(2)}}{2\epsilon}\right)^{r+1}\right\} \\ &-\frac{b\epsilon}{2\epsilon_1}\left\{\left(\frac{x_1+\epsilon_1+\epsilon-x^{(2)}}{2\epsilon}\right)^2 - \left(\frac{x_1-\epsilon_1+\epsilon-x^{(2)}}{2\epsilon}\right)^2\right\}, \end{aligned} & \begin{aligned} &\text{if } x^{(2)} - \epsilon + \epsilon_1 < x_1 \\ &< x^{(2)} + \epsilon - \epsilon_1; \end{aligned} \\ \begin{aligned} &\lambda - f_1 + m_L + q(m_H - m_L) + x_1 \\ &-\frac{\epsilon}{\epsilon_1}\frac{b}{2}\left\{1 - \left(\frac{x_1-x^{(2)}-\epsilon_1+\epsilon}{2\epsilon}\right)^2\right\} \\ &+\frac{\epsilon}{\epsilon_1}\frac{(1-q)(m_H-m_L)}{r+1}\left\{1 - \left(\frac{x_1-x^{(2)}-\epsilon_1+\epsilon}{2\epsilon}\right)^{r+1}\right\} \\ &+\left\{(1-q)(m_H - m_L) - b\right\}\frac{x_1-x^{(2)}-\epsilon+\epsilon_1}{2\epsilon_s}, \end{aligned} & \begin{aligned} &\text{if } x^{(2)} + \epsilon - \epsilon_1 \leq x_1 \\ &\leq x^{(2)} + \epsilon + \epsilon_1; \end{aligned} \\ \lambda - f_1 + x_1 + m_H - b, & \text{if } x_1 > x^{(2)} + \epsilon + \epsilon_1. \end{cases} \tag{26}$$

We can see that the expression of $u_1(x_1)$ is quite similar to equation (14).[20] Thus, by following the same procedures as in the proofs of the results in the main body, we can obtain similar results as well.

H Extension: Payoff Reduction of Voluntary Adopters after New Regulation

In the base model, we assume that new regulation does not reduce a voluntary adopter's market benefit from better reputation. Alternatively, one might argue that some environmentally conscious consumers do not care about a firm's voluntary adoption; instead they care only about whether a firm uses the green technology or not. In this case, new regulation might reduce a voluntary adopter's payoff because a firm that is forced to adopt the green technology by new regulation might steal some environmentally conscious consumers from voluntary adopters.

In this case, to model diffusion of consumer sentiment, we assume that β ($\in [0,1]$) portion of the market benefit from adopting a new green technology realizes in period 2, and $(1-\beta)$ portion realizes in period 3. In period 2, a firm that adopts the technology voluntarily receives $\beta(\theta - b\alpha)$, and a firm that does not adopt the technology receives zero. If new regulation is not enforced in period 3, then the proportion of adopters is still α. In this case, a firm that has adopted the technology receives $(1-\beta)(\theta - b\alpha)$, and a firm that has not adopted the technology receives zero in period 3. If new regulation is enforced in period 3, then all firms are forced to adopt the technology and the proportion of adopters is 1. Therefore, all firms receive $(1-\beta)(\theta - b)$ in period 3. If a firm adopts the technology in period 2, its payoff is $\pi_i(1;\theta,\alpha) = -f_L + \beta(\theta - b\alpha) + \{q + (1-q)\alpha^r\}\{(1-\beta)(\theta - b) + m_H\} + (1 - q - (1-q)\alpha^r)\{(1-\beta)(\theta - b\alpha) + m_L\}$. If a firm does not adopt the technology in period 2, its payoff is $\pi_i(0;\theta,\alpha) = \{q + (1-q)\alpha^r\}\{(1-\beta)(\theta - b) + m_H - f_H\}$. We can write $u_i(\theta,\alpha) = \pi_i(1;\theta,\alpha) - \pi_i(0;\theta,\alpha)$ as follows:

$$
\begin{aligned}
u_i(\theta,\alpha) \;=\; & -f_L + m_L + q(f_H - m_L) + (\theta - b\alpha)\{1 - q(1-\beta)\} \\
& + (1-q)\alpha^r\{f_H - m_L - (1-\beta)(\theta - b\alpha)\}.
\end{aligned}
$$

[20] If $x_1 \le x^{(2)} - \epsilon - \epsilon_1$ or $x_1 \ge x^{(2)} + \epsilon + \epsilon_1$, the expression of $u_1(x_1)$ is the same as $u_1(x_1)$ in (14). If $x^{(2)} - \epsilon - \epsilon_1 \le x_1 \le x^{(2)} - \epsilon + \epsilon_1$, there is an additional factor of $\frac{\epsilon}{\epsilon_1}$ for the terms that contain $\frac{x_1 - x^{(2)}}{2\epsilon}$ in (26), and the constant 1 in (14) is replaced by $\frac{\epsilon_1+\epsilon}{2\epsilon}$ in (26). If $x^{(2)} + \epsilon - \epsilon_1 \le x_1 \le x^{(2)} + \epsilon + \epsilon_1$, the term $\frac{x_1 - x^{(2)}}{2\epsilon}$ in (14) is replaced by $\frac{x_1 - x^{(2)} - \epsilon_1 + \epsilon}{2\epsilon}$ in (26), and there is also an additional factor $\frac{\epsilon}{\epsilon_1}$ for the terms that contain $\frac{x_1 - x^{(2)} - \epsilon_1 + \epsilon}{2\epsilon}$. These differences only change the magnitudes of affected terms, not their signs. If $x^{(2)} - \epsilon + \epsilon_1 \le x_1 \le x^{(2)} + \epsilon - \epsilon_1$, the expression of $u_1(x_1)$ in (26) is different from (14). However, the substitutability effect modeled by the negative term $-\frac{b\epsilon}{2\epsilon_1}\{(\frac{x_1+\epsilon_1+\epsilon-x^{(2)}}{2\epsilon})^2 - (\frac{x_1-\epsilon_1+\epsilon-x^{(2)}}{2\epsilon})^2\}$ and the complementarity effect modeled by the positive term $\frac{(1-q)(m_H-m_L)\epsilon}{(r+1)\epsilon_1}\{(\frac{x_1+\epsilon_1+\epsilon-x^{(2)}}{2\epsilon})^{r+1} - (\frac{x_1-\epsilon_1+\epsilon-x^{(2)}}{2\epsilon})^{r+1}\}$ still share a lot of similarities with those in (14) and the qualitative intuitions are similar.

Similarly, we obtain the expression of $u_1(\theta, \alpha)$:

$$\begin{aligned} u_1(\theta, \alpha) &= \lambda - f_1 + m_L + q\{m_H - m_L - b(1-\beta)\} + \theta - \{1 - q(1-\beta)\} b\alpha \\ &\quad + \alpha^r (1-q)\{m_H - m_L - b(1-\beta)(1-\alpha)\}. \end{aligned}$$

The above two expressions are similar to the expressions of $u_i(\theta, \alpha)$ and $u_1(\theta, \alpha)$ in (1) and (2) of the main body, except that the coefficients of a few terms are slightly different. Specifically, there is an additional factor $\{1 - q(1-\beta)\} > 0$ for the coefficients of α in the above two expressions. This additional factor does not change the signs of the coefficients. The coefficients for $\alpha^r (1-q)$ in the above two expressions become $\{f_H - m_L - (1-\beta)(\theta - b\alpha)\}$ in $u_i(\theta, \alpha)$ and $\{m_H - m_L - b(1-\beta)(1-\alpha)\}$ in $u_1(\theta, \alpha)$. As long as $(1-\beta)$ is sufficiently small, the coefficients for $\alpha^r (1-q)$ remain positive. As a result, all the qualitative insights obtained in §4 and §5 continue to hold if $(1-\beta)$ is sufficiently small (i.e., a firm that is forced to adopt a new green technology does not attract many environmentally conscious consumers), although the specific values of thresholds are different in this case.

I Extension: Single Representative Firm in Period 2

In this section, we use a single representative firm to model the whole industry. Let firm 2 denote the representative firm. To be consistent with the base model, we assume that the size of firm 1 is very small such that the voluntary adoption level is determined by the adoption in period 2. If firm 2 adopts the technology, then $\alpha = 1$. In this case, the government will enforce the new standard with certainty in period 3. If firm 2 does not adopt the technology, then $\alpha = 0$ and the government will not enforce the new standard in period 3. Firm 2 adopts the technology if and only if $x_2 \geq x^{(2)}$. To be consistent with the base model, we assume that $x^{(2)}$ increases with r. The following lemma shows how firm 1's threshold changes with r.

Lemma O7 *Firm 1's threshold* $x_{aggr}^{(1)}$ is nonincreasing with r if and only if $b > (1-q)(m_H - m_L)$.

Proof. We first derive the expression of firm 1's expected gain for a given signal x_1. We then use the expression to complete the proof.

Denote by β the probability that firm 2 will adopt the technology. If firm 2 adopts the technology, firm 1's gain for developing the technology for a given θ is $u_1(\theta) = \lambda - f_1 + m_H + \theta - b$. If firm 2 does not adopt the technology, firm 1's gain is $u_1(\theta) = \lambda - f_1 + m_L + q(m_H - m_L) + \theta$. So firm 1's expected gain for given θ and β is

$$u_1(\theta, \beta) = \lambda - f_1 + m_L + q(m_H - m_L) + \theta - \{b - (1-q)(m_H - m_L)\}\beta.$$

We next use this expression to derive $u_1(x_1)$, firm 1's expected gain for a given signal x_1.

For a given θ, $x_2 = \theta + \widetilde{\varepsilon}_2$ is uniformly distributed on $[\theta - \epsilon, \theta + \epsilon]$. Since firm 2 adopts the technology if $x_2 > x^{(2)}$, the expression for β is as follows:

$$\beta = \begin{cases} 0 & \text{if } \theta < x^{(2)} - \epsilon; \\ \frac{\theta + \epsilon - x^{(2)}}{2\epsilon} & \text{if } x^{(2)} - \epsilon \leq \theta \leq x^{(2)} + \epsilon; \\ 1 & \text{if } \theta > x^{(2)} + \epsilon. \end{cases}$$

For a given x_1, firm 1's posterior belief of θ is a uniform distribution on $[x_1 - \epsilon, x_1 + \epsilon]$. By following the same procedure as in the proof of Proposition 1(a), we can obtain $u_1(x_1)$ as follows:

$$u_1(x_1) = \begin{cases} \lambda - f_1 + m_L + q(m_H - m_L) + x_1 & \text{if } x_1 \leq x^{(2)} - 2\epsilon; \\ \begin{array}{l} \lambda - f_1 + m_L + q(m_H - m_L) + x_1 \\ -\frac{b-(1-q)(m_H - m_L)}{2}\left(\frac{x_1 - x^{(2)} + 2\epsilon}{2\epsilon}\right)^2 \end{array} & \text{if } x^{(2)} - 2\epsilon < x_1 < x^{(2)}; \\ \begin{array}{l} \lambda - f_1 + m_L + q(m_H - m_L) + x_1 \\ -\frac{b-(1-q)(m_H - m_L)}{2}\left\{1 - \left(\frac{x_1 - x^{(2)}}{2\epsilon}\right)^2\right\} \\ -\{b - (1-q)(m_H - m_L)\}\left(\frac{x_1 - x^{(2)}}{2\epsilon}\right) \end{array} & \text{if } x^{(2)} \leq x_1 < x^{(2)} + 2\epsilon; \\ -f_1 + \lambda + m_H + x_1 - b & \text{if } x_1 \geq x^{(2)} + 2\epsilon. \end{cases}$$

By following the same procedure as in the proof of Proposition 1(b), we can prove that $x_{aggr}^{(1)}$ is nonincreasing with r if and only if $b > (1-q)(m_H - m_L)$. □

Lemma O7 suggests that a smaller r discourages firm 1 from developing the technology if and only if $b > (1-q)(m_H - m_L)$, where $(1-q)(m_H - m_L)$ is a constant and does not change with r. Once the value of b is given, more aggressive regulation (smaller r) either always discourages or always encourages innovation; there is no way the government can change that. However, in the main body, Proposition 3 shows that a smaller r discourages firm 1 from developing the technology if and only if $b > b_x^*$, where b_x^* is a function of r. In this case, it is possible for the government to change how more aggressive regulation affects innovation. For example, consider a given b that is just slightly larger than $(1-q)(m_H - m_L)$ in Figure 10. In the single firm case, more aggressive regulation always discourages innovation because $b > (1-q)(m_H - m_L)$. However, in our base model case, if r is sufficiently small, then $b < b_x^*$ and more aggressive regulation encourages innovation; if r is sufficiently large, then $b > b_x^*$ and more aggressive regulation discourages innovation.

J Extension: Heterogeneous Technology Payoffs

In the main body we study a case in which firm i observes a noisy signal x_i of the maximum payoff θ. Since x_i is the sum of θ and a random noise $\widetilde{\varepsilon}_i$, all firms' signals are correlated. In this section we study a case in which firms have different maximum payoffs. Firm i's payoff from voluntary adoption is given as $\theta_i - b\alpha$. We assume θ_i is uniformly distributed on $\left[0, \overline{\theta}\right]$. The distribution of θ_i is known to every firm. To get a closed-form solution, we focus on the case with $r = 1$. We can obtain similar results for $r \neq 1$, but the analysis is much more complicated. We show the equilibrium in period 2 in the following lemma.

Lemma O5 *The equilibrium in period 2 is as follows:*
(i) If $b - (f_H - f_L) < 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) > \overline{\theta}$*, then there are three equilibria: All firms adopt the technology, no firms adopt the technology, or firms with* $\theta_i \geq \frac{b - f_H + f_L}{\overline{\theta} + b - (1-q)(f_H - m_L)}\overline{\theta}$ *adopt the technology.*
(ii) If $b - (f_H - f_L) \leq 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) \leq \overline{\theta}$*, then there is one equilibrium: All firms adopt the technology.*
(iii) If $b - (f_H - f_L) \geq 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) \geq \overline{\theta}$*, then there is one equilibrium: No firms adopt the technology.*
(iv) If $b - (f_H - f_L) > 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) < \overline{\theta}$*, then there is one equilibrium: Firms with* $\theta_i \geq \frac{b - f_H + f_L}{\overline{\theta} + b - (1-q)(f_H - m_L)}\overline{\theta}$ *adopt the technology.*

Proof. Following the same procedure as in §3 of the main body, we obtain the expected gain of firm i:

$$u_i(\theta_i, \alpha) = \theta_i - \alpha\{b - (1-q)(f_H - m_L)\} + q(f_H - m_L) - (f_L - m_L). \tag{27}$$

We next use this expression to prove the four cases in Lemma O5.
(i) Firm i adopts the technology if its expected gain is nonnegative. Using (27) we get $u_i(\theta_i, 1) = \theta_i + f_H - f_L - b$. So $u_i(\theta_i, 1) \geq 0$ simplifies to $\theta_i \geq b - (f_H - f_L)$. Since $b - (f_H - f_L) < 0$ and $\theta_i \in \left[0, \overline{\theta}\right]$, $u_i(\theta_i, 1) \geq 0$ for any θ_i. Firm i's expected gain is nonnegative if all other firms adopt. Thus all firms adopt the technology is an equilibrium.

Firm i does not adopt the technology if its expected gain is nonpositive. Using (27) we get $u_i(\theta_i, 0) = \theta_i + q(f_H - m_L) - (f_L - m_L)$. So $u_i(\theta_i, 0) < 0$ simplifies to $\theta_i < f_L - m_L - q(f_H - m_L) = q(f_L - f_H) + (1-q)(f_L - m_L)$. Since $q(b - f_H + f_L) + (1-q)(f_L - m_L) > \overline{\theta}$ and $\theta_i \in \left[0, \overline{\theta}\right]$, $u_i(\theta_i, 0) \leq 0$ for any θ_i. Firm i's expected gain is nonpositive if no other firms adopt. Thus no firms adopt the technology is an equilibrium.

A possible equilibrium is that a firm will adopt the technology if and only if $\theta_i \geq \theta^{(2)}$. In this case $\alpha = \left(\overline{\theta} - \theta^{(2)}\right)/\overline{\theta}$. Solving $u_i(\theta^{(2)}, \alpha) = 0$ yields $\theta^{(2)} = \frac{b - f_H + f_L}{\overline{\theta} + b - (1-q)(f_H - m_L)}\overline{\theta}$. We can show that the constraint $0 < \theta^{(2)} < \overline{\theta}$ hold if one the following two conditions are satisfied: (I) $b - (f_H - f_L) > 0$ and $q(f_L - f_H) + (1-q)(f_L - m_L) < \overline{\theta}$; (II) $b - (f_H - f_L) < 0$ and $q(f_L - f_H) + (1-q)(f_L - m_L) > \overline{\theta}$. Condition (II) is satisfied in this case.

We can prove (ii), (iii), and (iv) following the same procedure as in the proof of part (i). □

In case (i), there are multiple equilibria in period 2. It is quite similar to the complete information case with multiple equilibria. Multiple equilibria have weak predictive power because we do not know which equilibrium might be reached. We next show the equilibrium in period 1 in the following Lemma.

Lemma O6 *The equilibrium in period 1 is as follows:*
(i) If $b - (f_H - f_L) < 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) > \overline{\theta}$*, then there are three equilibria: If firm 1 believes that all firms will adopt the technology, it develops the technology if and only if* $\theta_1 \geq f_1 - \lambda - m_H + b$*; if firm 1 believes that no firms will adopt the technology, then it develops the technology if and only if* $\theta_1 \geq f_1 - \lambda - m_L - q(m_H - m_L)$*; if firm 1 believes only a proportion of firms will adopt the technology, then it develops the technology if and only if* $\theta_1 \geq f_1 - \{(1-q)(m_H - m_L) - b\}\frac{\overline{\theta} - q(f_L - f_H) - (1-q)(f_L - m_L)}{\overline{\theta} + b - (1-q)(f_H - m_L)} - \lambda - m_L - q(m_H - m_L)$.
(ii) If $b - (f_H - f_L) \leq 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) \leq \overline{\theta}$*, then firm 1 develops the technology if and only if* $\theta_1 \geq f_1 - \lambda - m_H + b$.
(iii) If $b - (f_H - f_L) \geq 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) \geq \overline{\theta}$*, then firm 1 develops the technology if and only if* $\theta_1 \geq f_1 - \lambda - m_L - q(m_H - m_L)$.
(iv) If $b - (f_H - f_L) > 0$ *and* $q(f_L - f_H) + (1-q)(f_L - m_L) < \overline{\theta}$*, then firm 1 develops the technology if and only if* $\theta_1 \geq f_1 - \{(1-q)(m_H - m_L) - b\}\frac{\overline{\theta} - q(f_L - f_H) - (1-q)(f_L - m_L)}{\overline{\theta} + b - (1-q)(f_H - m_L)} - \lambda - m_L - q(m_H - m_L)$.

Proof. Following the same procedure as in §3 of the main body, we obtain the expected gain of firm 1:

$$u_1(\theta_1, \alpha) = \lambda - f_1 + m_L + q(m_H - m_L) + \theta - b\alpha + \alpha(1-q)(m_H - m_L). \tag{28}$$

We next use this expression to prove the four cases in Lemma O6.
(i) If firm 1 believes that all firms will adopt the technology, then $\alpha = 1$. Using (28) we get $u_1(\theta_1, 1) = \lambda - f_1 + m_H + \theta_1 - b$. So $u_1(\theta_1, 1) \geq 0$ simplifies to $\theta_1 \geq f_1 - \lambda - m_H + b$. Similarly, we get $u_1(\theta_1, 0) = \lambda - f_1 + m_L + q(m_H - m_L) + \theta$. And $u_1(\theta_i, 0) \leq 0$ simplifies to $\theta_i \leq f_1 - \lambda - m_L - q(m_H - m_L)$.

If firm 1 believes that firms with $\theta_i \geq \frac{b - f_H + f_L}{\overline{\theta} + b - (1-q)(f_H - m_L)}\overline{\theta}$ will adopt the technology, then

$$\alpha = \left(\bar{\theta} - \frac{b - f_H + f_L}{\bar{\theta} + b - (1-q)(f_H - m_L)}\bar{\theta}\right) / \bar{\theta} = \frac{\bar{\theta} - q(f_L - f_H) - (1-q)(f_L - m_L)}{\bar{\theta} + b - (1-q)(f_H - m_L)},$$

$$u_1(\theta_1, \alpha) = \lambda - f_1 + m_L + q\,(m_H - m_L) + \theta + \{(1-q)\,(m_H - m_L) - b\}\,\frac{\bar{\theta} - q(f_L - f_H) - (1-q)(f_L - m_L)}{\bar{\theta} + b - (1-q)(f_H - m_L)},$$

and the solution of $u_1(\theta_1, \alpha) > 0$ is

$$\theta_1 \geq f_1 - \{(1-q)\,(m_H - m_L) - b\}\,\frac{\bar{\theta} - q(f_L - f_H) - (1-q)(f_L - m_L)}{\bar{\theta} + b - (1-q)(f_H - m_L)} - \lambda - m_L - q\,(m_H - m_L).$$

Following a similar procedure as in the proof of part (i), we can prove parts (ii)-(iv). □

Lemma O6 suggests that in the case of uncorrelated payoffs among firms, the equilibrium in period 1 is different from that in the case of correlated payoffs. With correlated payoffs, it is possible that the expected gain decreases with the payoff signal x_1. As a result, firm 1 may develop the technology if x_1 is relatively small, but choose not to develop the technology if x_1 is relatively large. This happens because firm 1 updates its beliefs on the expected value of α based on x_1: If x_1 increases, then firm 1 expects that more firms will adopt the technology and there will be more competing firms, and a larger number of competing firm can discourage firm 1 from developing the technology. However, in the case of uncorrelated payoffs, the expected gain increases monotonically with θ_1. There is only one threshold, and firm 1 develops the technology if its payoff is higher than this threshold. Since the distribution of θ_i is known to firm 1 and it does not change as θ_1 changes, firm 1's belief on the expected value of α does not change with θ_1. The complementarity and substitutability effects are constant for firm 1.

Additional Reference

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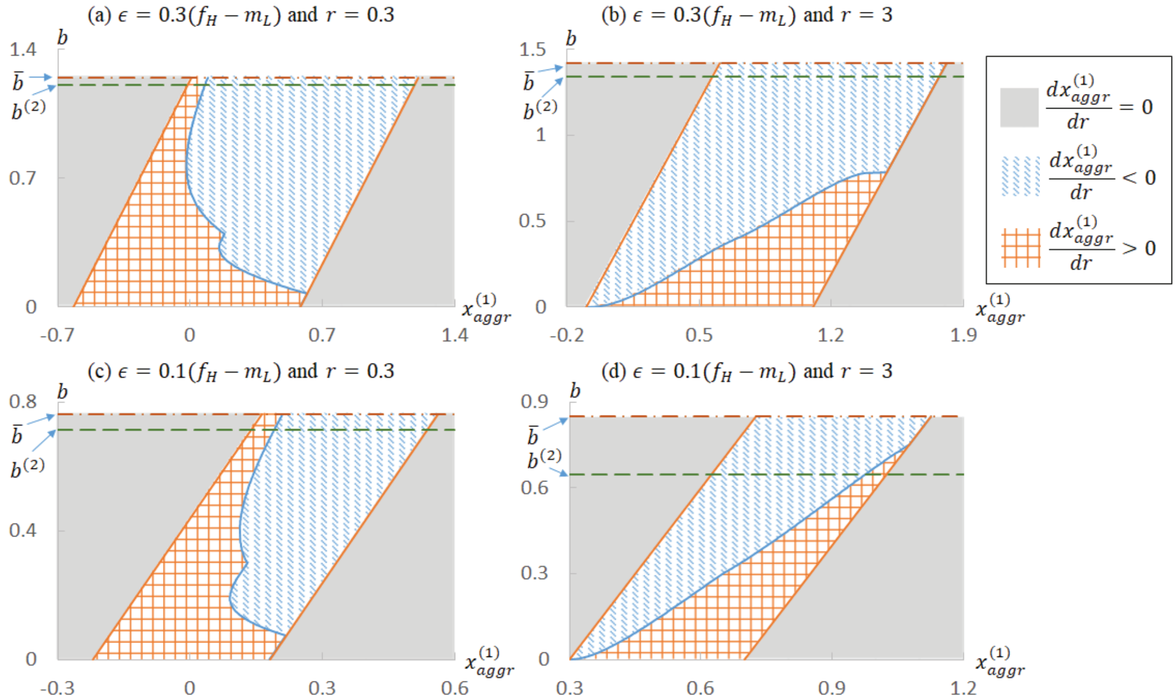

Figure 4: The Impact of Regulation Aggressiveness (r) on Firm 1's Threshold ($x_{aggr}^{(1)}$)
Notes. Other parameter values: $f_H = 2$, $f_L = 1$, $m_H = -1$, $m_L = -2$.

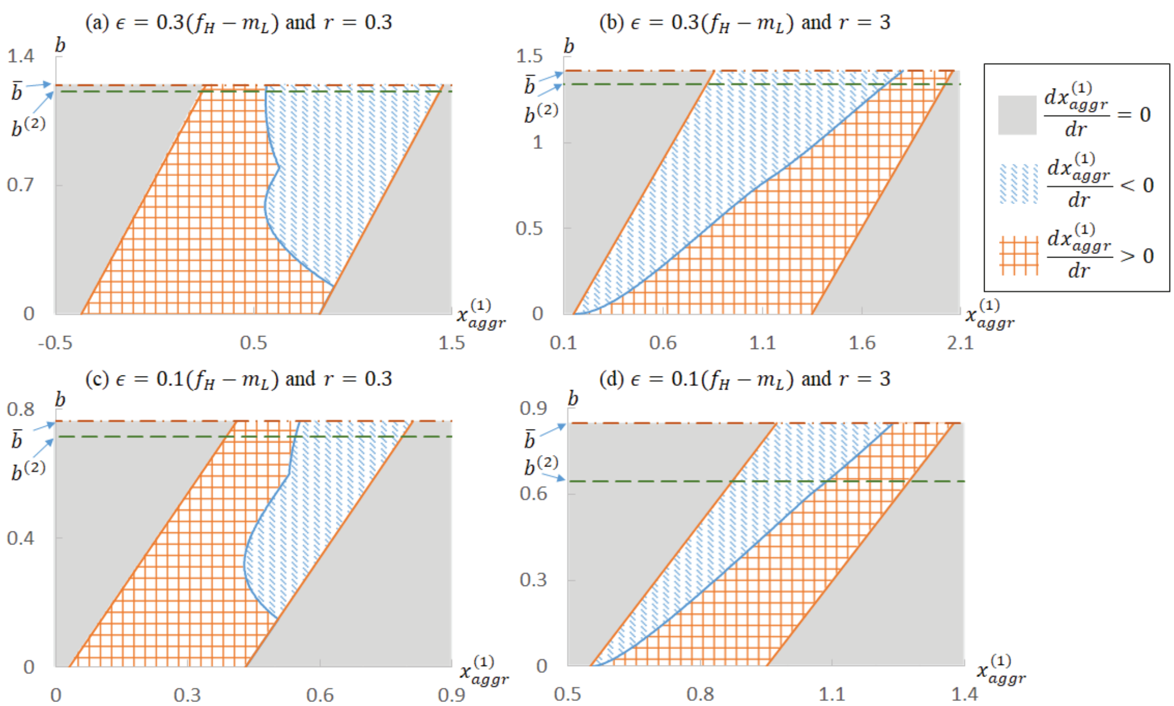

Figure 5: The Impact of Regulation Aggressiveness (r) on Firm 1's Threshold ($x_{aggr}^{(1)}$)
Notes. Other parameter values: $f_H = 2$, $f_L = 0$, $m_H = 0$, $m_L = -2$.

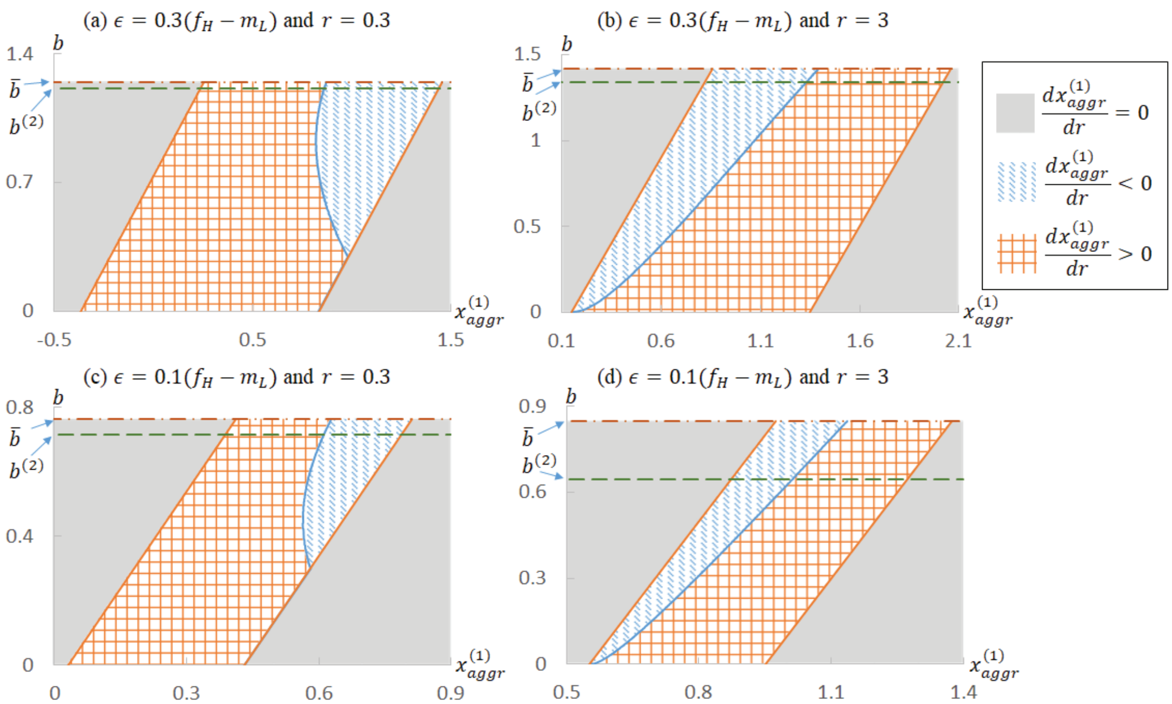

Figure 6: The Impact of Regulation Aggressiveness (r) on Firm 1's Threshold ($x_{aggr}^{(1)}$)

Notes. Other parameter values: $f_H = 0$, $f_L = 0$, $m_H = 0$, $m_L = -2$.

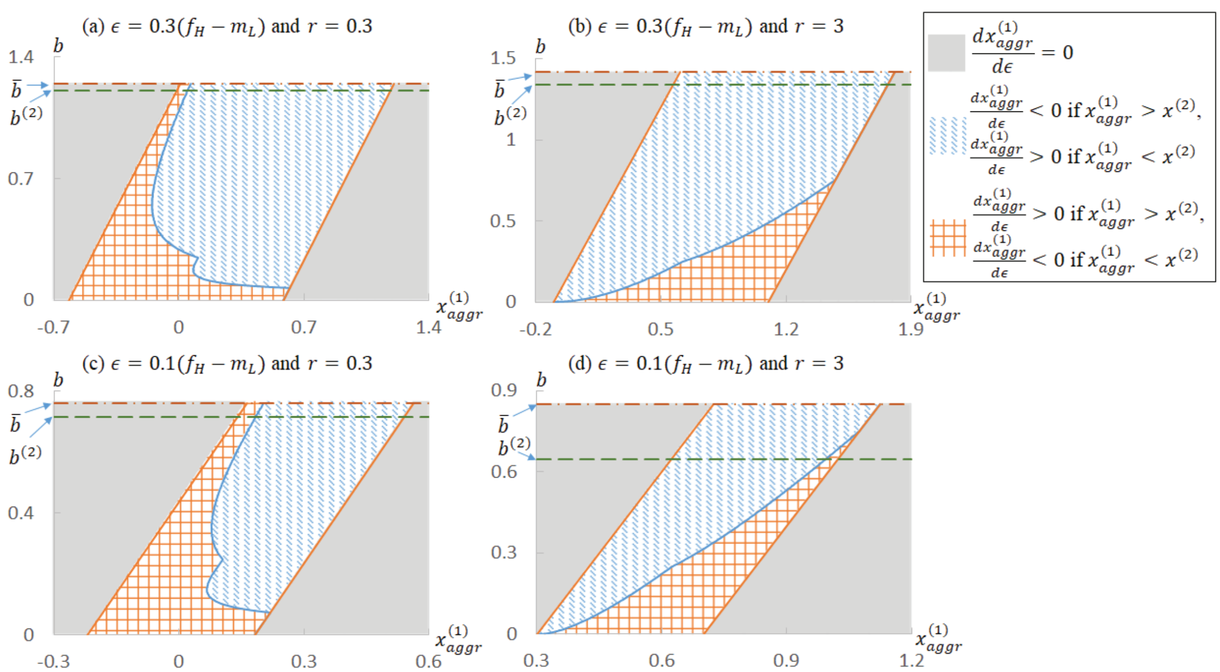

Figure 7: The Impact of the Level of Uncertainty (ϵ) on Firm 1's Threshold ($x_{aggr}^{(1)}$)

Notes. Other parameter values: $f_H = 2$, $f_L = 1$, $m_H = -1$, $m_L = -2$.

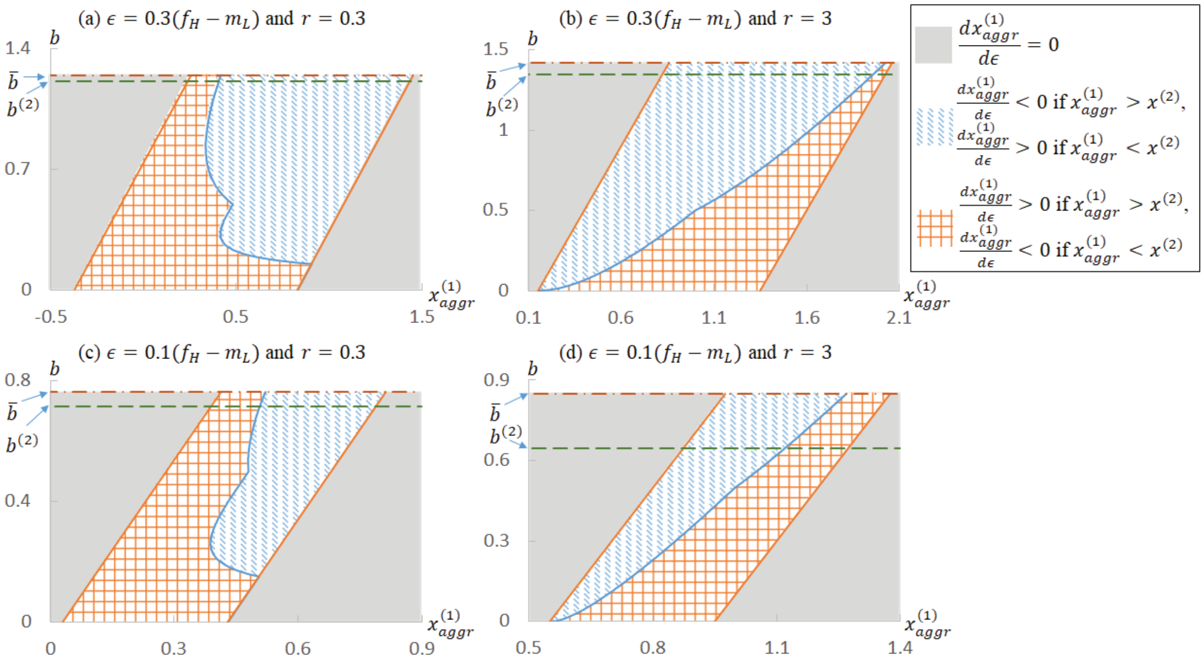

Figure 8: The Impact of the Level of Uncertainty (ϵ) on Firm 1's Threshold ($x_{aggr}^{(1)}$)
Notes. Other parameter values: $f_H = 2$, $f_L = 0$, $m_H = 0$, $m_L = -2$.

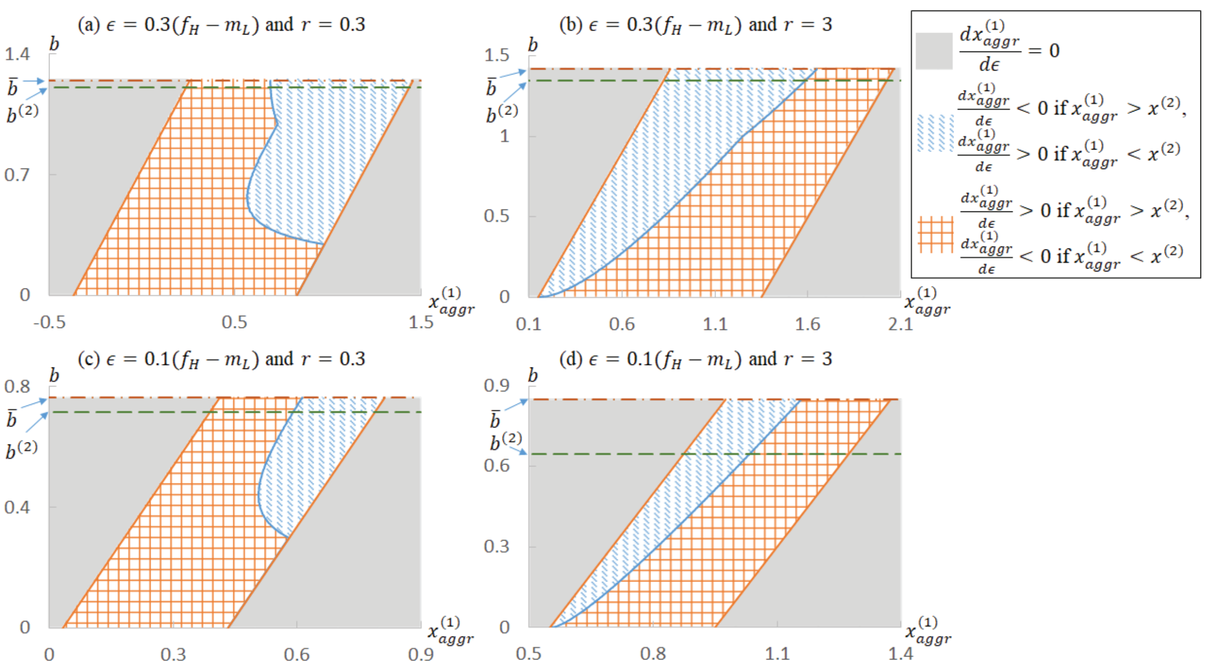

Figure 9: The Impact of the Level of Uncertainty (ϵ) on Firm 1's Threshold ($x_{aggr}^{(1)}$)
Notes. Other parameter values: $f_H = 0$, $f_L = 0$, $m_H = 0$, $m_L = -2$.

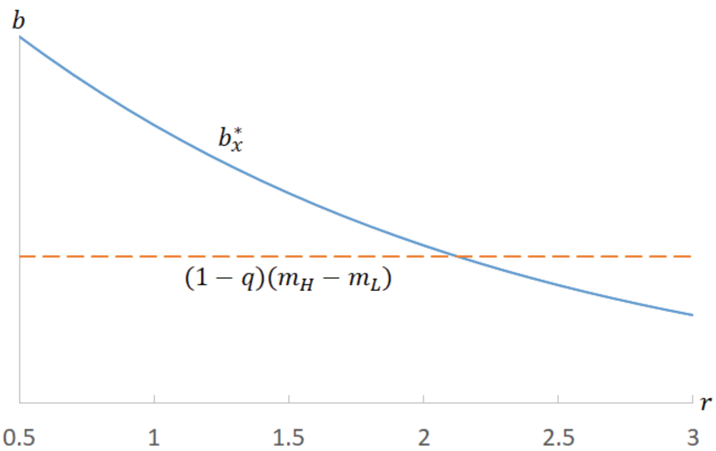

Figure 10: The Thresholds Above Which More Aggressive Regulation Discourages Innovation

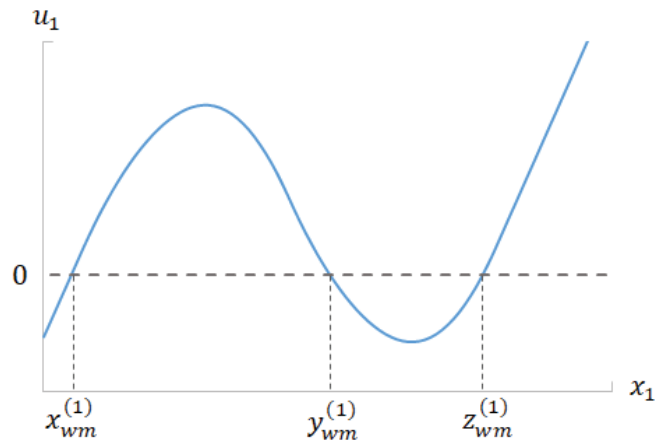

Figure 11: Firm 1's Expected Gain (u_1) When the Government Maximizes Welfare
Notes. Parameter values: $b = 2$, $\widehat{r} = 0.5$, $\lambda = 3$, $f_1 = 1.2$, $f_L = 1$, $f_H = 2$, $m_H = -1$, $m_L = -2$, $e = 6$, $\epsilon = 0.4$, $\widetilde{f}_r$ follows a gamma distribution with both shape and scale parameters equal to 2.

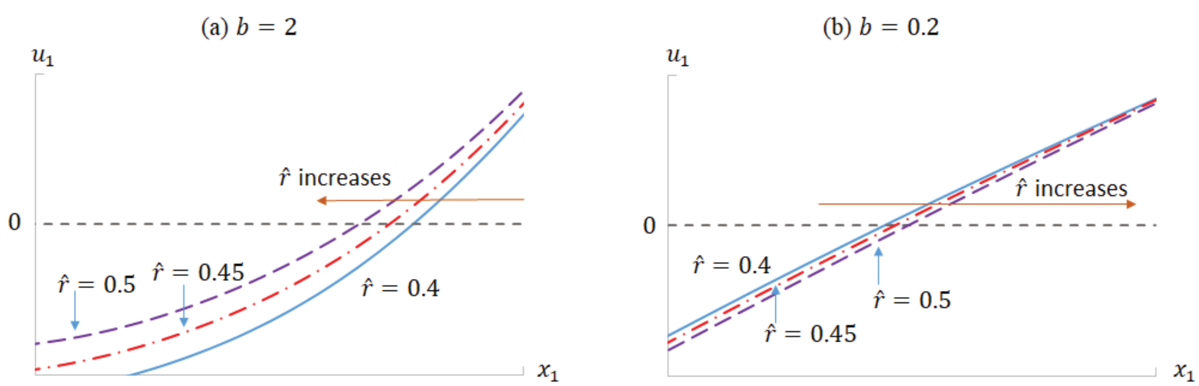

Figure 12: The Impact of Regulation Aggressiveness ($\widehat{r}$) on Firm 1's Threshold When the Government Maximizes Welfare
Notes. Other parameter values: the same as Figure 11 except $f_1 = 1.5$ and $\epsilon = 0.8$.

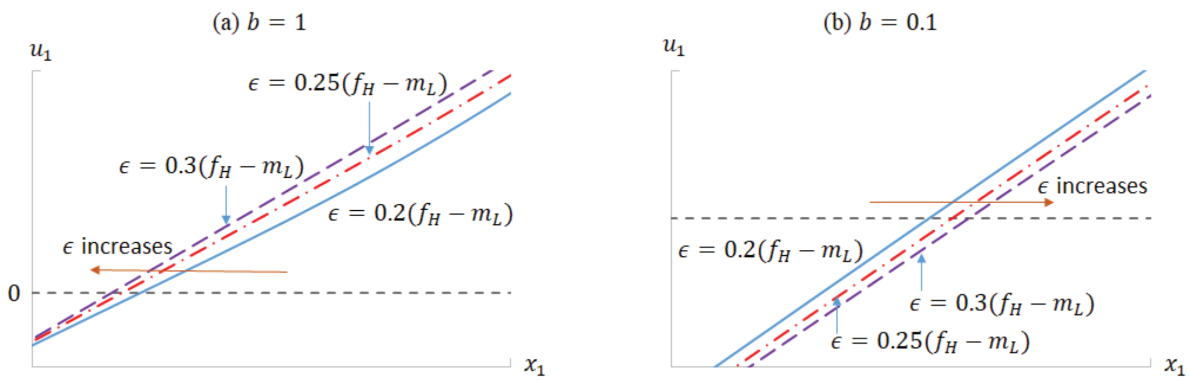

Figure 13: The Impact of the Level of Uncertainty (ϵ) on Firm 1's Threshold When the Government Maximizes Welfare

Notes. Other parameter values: the same as Figure 11 except $f_1 = 1.5$ and $\widehat{r} = 0.4$.