I Don't "Recall": The Decision to Delay Innovation Launch to Avoid Costly Product Failure

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Innovations embody novel features or cutting-edge components aimed at delivering desired customer benefits. Oftentimes, however, we observe the need to recall new products shortly after their introduction. Indeed, a firm may rush an innovation to market in an attempt to pre-empt rivals and capture early demand, yet in so doing forgo rigorous testing; thus subjecting itself to the risk of a product recall. To shed light on this phenomenon, we construct a dynamic game-theoretic model in which firms plan to launch their innovations. Each firm must decide whether to conduct time-consuming quality assurance testing, which ensures no defects or safety problems but delays the launch. If the innovation is released without such testing and a recall occurs, the firm incurs pecuniary costs and faces future reputation damage in marketing the recalled innovation. We investigate the strategic forces behind firms' testing and launch-timing decisions in this context. The analysis uncovers a novel mechanism, linked to the possibility of a rival going bankrupt, that causes firms to become more inclined to rush to market and take on the risk of product failure even as the negative consequences of a recall increase. The results further demonstrate how firms' desire to forgo testing exhibits an inverse-U pattern as consumers become more heterogeneous; and how competitive forces may induce both firms to forgo testing, even though the resulting profits are lower than had they both committed to conduct testing. The framework is extended to examine how product recall considerations affect firms' research and development (R&D) investments. Although, in general, post-innovation product failure discourages R&D effort, we identify conditions under which an increase in the recall probability stimulates firms to innovate. Several model extensions are presented and managerial implications are discussed.

Key words: innovation management; product recall; quality assurance testing; launch-timing; game theory

1. Introduction

The introduction of new products is an essential part of firms' business activities and serves as a cornerstone for long-term growth and survival (Bresnahan et al. 1997, Teece 2009). Guided by a firm's innovation strategy, new products offer novel features or attribute improvements as the outcome of research and development (R&D) initiatives. During the R&D process, firms typically dedicate some basic time and effort to conducting a set of quality assurance tests aimed at establishing the proper functionality and safety of their innovations. Yet once launched into the marketplace, we often observe the recall of new products. In the automobile industry, for example, more than 50 million vehicles were recalled in the United States in 2016, nearly three times as many as were sold that year (NHTSA 2018). The U.S. Consumer Product Safety Commission (CPSC) announces at least one product recall every day on average (New York Times 2016). This prevalence of product recalls suggests that firms may not always assign sufficient time and effort toward quality assurance prior to releasing their innovations.

Consider the following particular example. In August 2016, Samsung Electronics unveiled the Galaxy Note 7, a flagship smartphone packed with innovative features such as an iris scanner, high dynamic range (HDR) support, and extended battery life. By setting an aggressive launch date, Samsung was eager to capture demand from early enthusiasts and outmaneuver its primary rival Apple, which was planning to introduce the iPhone 7. At the time of release, the new Samsung device was deemed a success. Initial demand was high, breaking historical pre-order records and causing supply shortages (Reuters 2016). To Samsung's dismay, however, shortly after the debut a number of these devices were reported to overheat and catch fire within days of real-world use. Samsung quickly responded and issued a voluntary replacement program. Nonetheless, the crisis carried on as the replacement devices exhibited the same problem. Eventually, Samsung issued a full recall, pulling the 2.5 million devices that had been sold off the market and permanently suspending production (Time 2016). The consequences of the Galaxy Note 7 debacle were catastrophic. Samsung estimated the direct cost of the recall at $5.3 billion; in a survey of its customers, 34% responded that they would be reluctant to purchase another phone from the brand; and the company's stock price dropped by more than 8%, effectively removing $19 billion off its book value (Newsweek 2016).[1]

[1] In January 2017, Samsung acknowledged that insufficient testing prevented it from discovering the culprit inside the battery separator (https://news.samsung.com/us/a-look-at-our-process-quality-control/) and subsequently implemented a broad range of new quality and safety testing protocols (https://www.samsung.com/us/explore/committed-to-quality).

This example demonstrates the severe consequences that a product recall may entail, and highlights an important question commonly raised during the new product development process: How much testing should a firm conduct on a new product prior to its launch to ensure full safety and functionality? The dilemma is between delivering a rigorously vetted product vs. capturing early demand and profits. This is a non-trivial decision since there exists uncertainty over product failure and the implications of a resulting recall can be moderate or severe.

On the one hand, a firm can choose to conduct thorough quality assurance testing of various circumstances and conditions encountered in everyday product use. Such testing allows the firm to detect and correct potential sources of product failure, thereby avoiding the possibility of having to issue a recall. These tests, however, typically require a dedicated period of time to complete, resulting in a delay of the product launch. On the other hand, a firm may be tempted to forgo extensive quality assurance testing and rush to market, running only minimal, short-term lab tests that are insufficient to detect all possible shortcomings. By introducing its innovation immediately, the firm can pre-empt the competition and capture initial demand. These advantages, however, come at the risk of a recall due to product failure. A recall, when it occurs, could be detrimental both to consumers and to the firm. A faulty product, at a minimum, causes inconvenience to the unlucky customers who purchased it and, in worst-case scenarios, leads to injuries and fatalities. The firm not only incurs the direct cost of recalling the product (e.g., product collection, monetary reimbursement, and repairs/replacements), but may also incur other losses: damage to its brand equity associated with the innovation; a hit to firm valuation; and potential lawsuits and regulatory challenges. Furthermore, in instances when these costs are severe, the firm may exit the product market or even go out of business.[2]

Product recall considerations can also have implications for firms' willingness to ex-ante undertake innovation efforts. When uncertainty over proper innovation functionality is high and the repercussions of a product recall are severe, some firms may not find it worthwhile to invest in R&D in the first place. For instance, Apple opted to postpone the development of a foldable smartphone until rivals Samsung, Huawei, and Motorola fixed their shortcomings and the technology matured (Forbes 2019).

[2] Notable examples of bankruptcy following a recall include: Takada Corporation (June 2017), due to faulty airbag inflators; Owen's Corning (October 2000), due to products that contained unhealthy substances; and A. H. Robins Company (August 1985), due to faulty birth control devices.

In the automobile industry, Daimler decided to halt development of its fuel-cell electric vehicle, citing concerns about the proper functioning of its hydrogen technology at scale (Fortune 2017).

In this study, we shed light on how firms determine whether to conduct rigorous quality assurance testing when facing uncertainty over product failure and competitive pressures, as well as the implications of this decision for undertaking innovation efforts. Our analysis addresses the following specific research questions:

- Under what conditions do firms conduct vs. forgo time-consuming quality assurance testing of their innovation prior to launch? Are firms always more likely to conduct such testing as the negative consequences of a recall increase?
- What are the implications of firms' testing and launch-timing decisions on pricing and profits? How does greater heterogeneity in consumer preferences influence firms' decisions and profit levels?
- What is the relationship between the possibility of a product recall and firms' ex-ante willingness to innovate? Does an increase in the likelihood of post-launch product failure always depress firms' incentives to invest in R&D?

To answer these questions, we construct a dynamic game-theoretic model in which two horizontally differentiated firms plan to introduce their innovations into a market composed of consumers with heterogenous preferences. The firms decide, prior to launch, whether to conduct thorough quality assurance testing that guarantees the robustness of their innovations. They either elect to conduct such testing and delay the launch or choose to offer the innovation immediately and bear the probabilistic occurrence of a recall in the upcoming period. If the product fails and is recalled, we incorporate two detrimental consequences for the firm: the pecuniary costs of dealing with the product recall (direct cost) and the reputational damage the innovation may suffer in the ensuing period (indirect cost).

The analysis reveals four primary forces that drive firms' testing and launch-timing decisions. The first, termed *recall avoidance*, plays a role when the probability of new product failure is high or the costs associated with a recall are large. This force drives the firm to "play it safe" and delay the launch to ensure its innovation is fail-proof. However, when the potential consequences of a recall are limited and consumer benefits from the innovation are large, a *market pre-emption* effect kicks in, prompting the firm to "take on the risk" of skipping rigorous testing to enjoy the greater profits generated from launching its innovation as soon as possible. Interacting with these two countervailing forces is the impact of the competitive environment. If the potential loss from lagging behind the competition in the product space is significant, an *anti-lag incentive* stimulates a firm to forgo testing and rush to the market with its innovation. However, when firms take the same action (i.e., if either both test or both forgo testing), a "correlative" drawback emerges because the firms will offer equally advanced products in the first period (and possibly in the second). Hence, a *differentiation incentive* is also present and reflects a firm's motivation to distinguish its offering vis-à-vis the rival's by controlling the timing of innovation launch.

The interplay among these forces gives rise to three equilibria, depending on the failure probability of the innovation and the costs of dealing with a recall: (1) neither firm conducts testing and both launch the innovation immediately (*no-test equilibrium*); (2) both firms are prudent and conduct testing (*dual-test equilibrium*); or (3) only one firm conducts testing while its rival rushes to the market (*single-test equilibrium*).

The decision by both firms to forgo testing is driven by a combination of the competitive forces at play. When the market pre-emption force is substantial, a firm will have a strong incentive to launch its innovation early. Given this decision, the rival's profits will drop significantly if it decides to test (as it will have to offer its inferior legacy product in the first period). This triggers an anti-lag incentive for the rival, which, if strong enough, drives it to also prefer to skip testing and launch the innovation early. We further find that the no-test equilibrium region exhibits an inverse-U pattern—initially expanding and then shrinking—as the degree of consumer heterogeneity increases. Notably though, by forgoing testing the firms may be worse off than had they both been able to commit to testing (i.e., the firms face a prisoner's dilemma situation).

The analysis further reveals an interesting property of the no-test equilibrium. A more negative consequence of a recall (higher direct costs) may actually prompt two competing firms to release their innovations immediately—rather than serve to deter early introduction. This incentive to forgo testing is driven by the implicit benefit of recalls occurring probabilistically. Specifically, a firm "bets" on becoming a sole player in the market and enjoying monopoly-level profits in the ensuing period, if its rival cannot recover from a product recall and goes out of business. Hence, and somewhat counterintuitively, as the costs associated with a recall exceed a certain level, both firms may become more willing to launch their innovations early; rather than one of them delaying the launch to test its product. The intense competition that ensues, since both firms offer equally advanced products, limits the profit levels in the first period. Consequently, by rushing to market as well, a firm effectively lowers the profits of its rival, which would then go bankrupt in the event of a recall; thereby paving the way for the firm to become a monopolist in the second period (whereas the rival would have been able to withstand such a fate by earning higher profits if the firm had tested and thus launched its inferior legacy product instead).

The dual-test equilibrium emerges when consumers derive limited benefits from the innovation, a product recall is highly likely, and the negative consequences of a recall are severe. A strong recall-avoidance effect dominates the incentive to pre-empt the market, urging both firms to be cautious with their innovations. Lastly, when the consequences of a recall are intermediate, the single-test equilibrium is sustained. In this equilibrium, the market pre-emption effect prompts one firm to rush to the market. But the nontrivial possibility of incurring recall costs, as well as a desire to be vertically differentiated, dominate the anti-lag incentive for the rival and drive it to conduct testing. The two firms thus seek to distinguish their product offerings over time via the testing decision.

The basic framework is then extended to show how the potential for product failure and experiencing a recall affects firms' ex-ante incentives to invest in R&D. We find that, although post-innovation product failure generally suppresses the desire to innovate, there exists a mechanism that can prompt firms to be more willing to undertake R&D investment as the failure probability rises. Specifically, this occurs when (1) the benefits of product differentiation if only one firm endures a product recall are substantial or (2) the prospects of monopoly-level profits if the rival goes bankrupt as a result of a recall are very enticing. In these cases, exactly because the probability of new product failure increases, both firms are better off innovating rather than sticking to the mature product throughout the game.

The rest of the paper is organized as follows. Section 2 relates our work to relevant literature. Section 3 describes the model setup. Section 4 investigates firms' quality assurance testing strategies when confronted with the possibility of product failure and recalls. In Section 5, the framework is extended to examine firms' ex-ante R&D investment decisions. Section 6 discusses a series of extensions and robustness checks. Section 7 summarizes key findings, offers managerial implications, and discusses limitations.

2. Literature Review

Our study is related to four primary research streams: (1) the timing of new product introductions, (2) quality control, prototyping and product safety, (3) dealing with the aftermath of a product-harm crisis, and (4) new product R&D decisions. We discuss each of these streams in turn.

First, our study is connected to a broad body of research that models the launch-timing of innovations (Reinganum 1989, Krishnan and Ulrich 2001). Early work by Kamien and Schwartz (1972) finds that the optimal timing is determined by: the costs associated with compressing the development schedule (commonly referred to as "crashing" the project); the profit implications of delaying the launch; and the probability of a rival successfully innovating. Focusing on the time-to-market versus quality trade-off,[3] Cohen et al. (1996) and Bayus et al. (1997) show that rushing to market with a new product is not always beneficial and that the firm could be better off delaying the launch and utilizing that time to improve product quality. However, Morgan et al. (2001) demonstrate that this quality improvement incentive might not hold when a firm can repeatedly launch incrementally improved products.

In these papers, product quality increases over time such that a firm faces a trade-off between introducing a lower-quality product immediately vs. waiting to launch a more valued product later. This literature bears a similarity to our setup, in the sense that if a firm conducts testing it effectively guarantees delivering a robust product in the later period. However, there are a number of differences that separate our work from the traditional time-to-market research. In our setting, if a firm decides to rush to the market, it can *immediately* sell the better quality product. This upfront benefit, however, is accompanied by risking a product recall that (1) results in pecuniary costs that are proportional to the revenues gained from the early launch and (2) causes reputational damage to the firm's innovation in the future. Our study thus contributes to the aforementioned literature by exploring a novel perspective with respect to a firm's incentives to advance or delay the introduction of a new product, which differs from the quality improvement vs. timing trade-off.

A focus of our analysis is the role of testing to avoid product flaws and avert the risk of a recall. Hence, our work also bears on literature pertaining to quality testing and prototyping. The extant literature in this area follows two branches: design quality (during the R&D process) and conformance quality (during the manufacturing process). Design quality assurance is carried out during the development phase to resolve technical uncertainty over new features and involves building test models such as prototypes. Dahan and Mendelson (2001) and Thomke and Bell (2001), with their emphasis on improving design quality standards, investigate the optimal timing and frequency of such testing. Conformance quality

[3] Studies in marketing, operations research, and economics have surfaced other factors that affect new product launch timing (e.g., Eliashberg and Jeuland 1986, Datar et al. 1997, Narasimhan and Zhang 2000, Savin and Terwiesch 2005). We focus on the stream of research addressing the time versus quality trade-off due to its relevance to our work.

refers to the extent to which a manufactured product meets the design specifications (given quality standards) and is measured as the proportion of units produced that are not defective. Li and Rajagopalan (1998) consider the role of conformance quality assurance in the presence of learning effects and evaluate the cost-benefit trade-offs for continuous quality improvement.

While these papers assess the role of product testing during R&D and manufacturing, to our knowledge, there has been no careful modeling and evaluation of post-development, yet pre-mass-production, quality assurance effort. Such testing, which guarantees the safety and stability of a working version of an innovation, is commonly conducted in practice (e.g., automobile pre-production testing, mobile device stress testing, and software beta testing). Hence, we contribute to this literature stream by analyzing various factors that determine a firm's incentives to conduct pre-launch quality assurance testing.

A notable paper on a related topic is Iyer and Singh (2018), which examines a firm's decision to seek voluntary safety certification, prior to selling its product, as a means to raise consumer safety concerns. The firm's product is subject to experiencing a probabilistic failure, and through certification the firm attempts to alleviate the costs of compensating consumers for their injuries. The setting involves a monopolist marketing a new product that it is ex-ante endowed with, and thus there is no competition or product development in place. By contrast, our study accounts for the various consequences of a product failure and the firms' decision to prevent such a debacle (through quality assurance). Furthermore, we consider the strategic interaction between competing firms, the role of horizontal consumer preferences, and the firms' decision to ex-ante undertake R&D effort.

Third, our study is related to a growing body of empirical research on product-harm crises. A number of consequences stemming from product recalls have been studied, including brand equity (Dawar and Pillutla 2000), firm value (Chen et al. 2009), marketing-mix effectiveness (Van Heerde et al. 2007, Liu and Shankar 2015), and advertising spending (Gao et al. 2015). Despite the substantial evidence of the negative after-effects of product recalls, limited analytic research has examined firms' strategic incentives to avoid such risks. Hence, we contribute to this literature by shedding light on when firms should have greater impetus to avoid (or take on) product recall risks, how competition affects such decisions, and how the potential for a product recall impacts firms' motivation to invest in R&D.

Finally, our study relates to R&D investments under competition. Research in economics and marketing has investigated the rationale behind firms' decisions to differentiate their innovation paths across various contexts, including initial asymmetry in industry position, i.e., a technology gap (Cabral 2002, 2003), acquisition of product modification information (Iyer and Soberman 2000), market research and consumer heterogeneity in preferences (Lauga and Ofek 2009), retail channel acceptance and power relations with manufacturers (Luo et al. 2007), and voluntary disclosure of quality information (Guo and Zhao 2009). These papers illustrate various underlying motivations that influence competing firms' decision to differentiate via their innovation strategies. Our study contributes to this stream by introducing an alternative view: how the interplay between the desires to preempt the market, avoid a costly recall, not lag behind, and differentiate affect firms' calculus of whether to undertake new product development effort and when to launch their innovations.

3. Model Setup

This section formulates a dynamic model of quality assurance testing and product recalls under competitive pressures and horizontal heterogeneity in consumers' preferences.

3.1. Testing Decision

Consider two firms, indexed $i \in \{1, 2\}$, planning to introduce their independently developed innovations into a given market. The innovations add similar new benefits to the firms' existing offerings such that they are of greater value to consumers.[4] We denote the quality level of the existing generation, *mature product* by V and the quality level of the successive generation, *innovative product* by $V + B$, where B captures the enhanced desirability or extent of quality improvement delivered by the innovation.[5] For ease of exposition, we assume the products can be produced at zero marginal cost.

Before launching their innovations, the firms face a decision of whether to conduct rigorous and extensive quality assurance testing. Such testing takes time and effectively delays the launch, but allows detecting and fixing bugs or problems with the new product; thus ensuring that it is safe and works properly in a range of real-world settings. We index this decision by $QA \in \{0, 1\}$, where 1 denotes engaging in quality assurance testing and 0 denotes forgoing such testing and introducing the innovation immediately.

[4] In many industry contexts, new products offered by competing firms embody similar innovative benefits. Examples include multiple automakers that improve fuel efficiency, driver assistance, safety features, and infotainment systems; and smartphone companies that enhance 5G network connectivity, photo capabilities, screen quality, battery life, and charging speed. Though each firm may have its own version of the innovation, we abstract away from such idiosyncratic differences.

[5] In our model, "quality" is used as a summary variable that captures all benefit-relevant aspects of the product. All consumers place a greater value on products with a higher level of this quality variable.

To reflect the dynamic trade-off between launching immediately to seize early sales on the one hand, and delivering a rigorously vetted innovation on the other, we model a two-period game. The testing decision affects the nature of products a firm can sell in each period. Specifically, when a firm decides to conduct testing ($QA = 1$) in the first period ($t = 1$), it must delay the introduction of its innovation until the second period ($t = 2$) in order to complete the necessary checks and address possible shortcomings. To simplify the analysis, we assume that this period-long testing removes any defects and safety concerns associated with the innovation.[6] At $t = 1$, while the test is being conducted, the firm can sell its mature product, which has already been verified in the market as fail-proof.[7] By contrast, if a firm forgoes testing ($QA = 0$), it launches its innovation immediately at $t = 1$. However, the untested product carries a probability of failure θ during the period, where $\theta \in (0, 1)$ is identically and independently distributed across firms. The failure probability is assumed to be common knowledge for firms, reflecting the historical rate of product failure for the industry and/or the associated technology.

3.2. Product Failure and the Consequences of a Recall

If a firm forgoes testing and launches its innovation in the first period ($t = 1$), information on proper product functioning and possible defects is revealed through customer use over the course of the period. In the event that the innovation is found to be faulty, the firm is penalized in two ways: (1) it must bear the pecuniary costs associated with recalling all the products sold in the first period, and (2) its innovation suffers reputation damage in the ensuing period because consumers perceive it to be less reliable (or don't want to be associated with the product's brand name given the mishap).

The pecuniary penalty from having sold a product discovered to be defective, denoted by $\Delta > 0$, represents the *direct cost of a recall*. Given that the firm must execute a recall program to fix and/or reimburse customers for all products sold, this cost is in part a function of the firm's first-period sales.

[6] The results are robust to relaxing this assumption such that testing significantly reduces, but does not completely eliminate, the failure probability. We note that the firms in our study are assumed to have conducted some basic quality assurance testing during development; however, unless they commit significant time and effort to examine and stress test the innovation post development (during $t = 1$), they may overlook potential flaws before launch.

[7] In this study, we assume that when a product has been in the market for a full period, any significant problems or defects will be discovered and dealt with. Thus, the mature product, which was marketed in prior periods, is "bug-free." Similarly, if the innovation is launched at $t = 1$, then if it has any defects or safety issues, those would be detected through actual customer experiences and rectified prior to $t = 2$. Note here that, although the testing decision determines how potential product flaws will be revealed (i.e., during the testing phase vs. through in-market customer usage), the expense associated with remedying these flaws applies analogously to either scenario. Hence, including such an expense in the model would not change the results. See Section B.6 of the Online Appendix for more details.

Hence, we define the pecuniary penalty as $\Delta = \rho + \delta \cdot p_1 \cdot d_1 = \rho + \delta \cdot \pi_1$, where $\rho > 0$ captures the fixed cost of a recall and $\delta \in (0,1]$ expresses the degree of penalty per dollar generated from each product sold at $t = 1$. Through this formulation, we are able to capture an array of scenarios: (1) when $\delta \to 0$, the firm does not lose the entire revenue gained from selling the innovation, and is able to correct or replace defective parts at a modest cost; (2) when $\delta = 1$, a full buy-back of the defective product takes place (refunding all customers the price they paid); and (3) the parameter ρ, on top of any fixes and refunds to customers, captures all the administrative costs, including lawsuits, government fines, and expenses linked to notifying the public.

Once a recall takes place, if the firm cannot fully cover the direct costs—that is, if the pecuniary costs associated with a recall, Δ, exceed the profits generated at $t = 1$ (i.e., $\Delta > \pi_1 \Leftrightarrow \rho > (1-\delta) \cdot \pi_1$)—the firm goes bankrupt and exits the market. Under such an eventuality, the firm that experienced a recall, in effect, makes zero profits in both periods (i.e., firms have limited liability).[8]

If the firm experiences and withstands a recall (i.e., $\Delta \leq \pi_1$), consumers' perception of the innovative product and their trust in its quality and reliability are likely to be negatively affected. Specifically, let the value of a *recalled innovation* be $(V + B)(1 - \gamma)$, where the parameter $\gamma \in (0,1)$ captures consumers' disutility from purchasing a product that has previously been recalled. Thus, the decrease in product valuation, $(V + B)\gamma$, represents the *indirect cost of a recall*. When $\gamma \to 0$, the innovation's value does not drop by much at $t = 2$ and consumers ignore the fact that the product was previously recalled. However, when $\gamma \to 1$, consumers fully discount the innovation's value and do not trust the firm to have fully resolved the problems (or do not want to be associated with the product given its recall history). We also refer to the parameter γ as the "reputation damage" the firm's innovation suffers due to it being relaunched into the marketplace after a recall had been publicly exposed in the first period.[9]

We classify the product a firm sells, k, as belonging to one of three types: (1) a mature product denoted by $k = ma$, (2) an innovation that has not been recalled denoted by $k = in$, and (3) an innovation that has previously suffered a recall denoted by $k = rc$. Note that $k = in$ can apply to an innovation in either

[8] The results are robust to allowing firms to borrow from future profits (i.e., if bankruptcy depends on profits from both $t = 1$ and $t = 2$). We thank an anonymous reviewer for prompting us to include firms' limited liability in the model.

[9] The results are robust to modeling the value of a recalled innovation in the second period as $V + B(1 - \gamma)$, i.e., only the innovative benefits are affected by a recall. Note that, in this case, the value of a recalled innovation is always higher than that of a mature product. Hence, our current setup, which allows the recalled innovation to confer less or more value than a mature product, embeds the alternative formulation. See also Section B.7 of the Online Appendix, which discusses the role of reputation damage in our model and the implications of setting $\gamma = 0$.

period (at $t=2$ this applies if testing took place or if the innovation was launched at $t=1$ but a recall did not occur), while $k=rc$ is only relevant for an innovation at $t=2$ following a recall.

3.3. Consumer Utility

The market is composed of a unit mass of consumers who are heterogeneous in their preference for different brands (i.e., a horizontal market structure). Consumers are distributed uniformly along a line segment in the preference space, $x \sim U[0,1]$. The two firms $i \in \{1,2\}$ are situated at each endpoint of the unit consumer interval, i.e., at $x=0$ and $x=1$ (Hotelling 1929). A consumer at preference location x incurs disutility τx when buying firm 1's product and disutility $\tau(1-x)$ when buying firm 2's product. The disutility reflects the consumer's "dissatisfaction" at purchasing from a firm that is distant from their ideal point. The parameter τ represents the sensitivity to brand mismatch and thus captures the degree of consumer heterogeneity.

Consumers buy at most one good and maximize their utility conditional on the products offered and the prices set by the firms. More formally, the utility a consumer at location x derives from purchasing firm i's product k^i at price p^i is given by

$$u^i = \begin{cases} q(k^i) - p^i - \tau x & \text{if } i=1, \\ q(k^i) - p^i - \tau(1-x) & \text{if } i=2, \end{cases} \tag{1}$$

where $q(k^i)$ denotes the consumer's quality valuation for product type $k^i \in \{ma, in, rc\}$, with $q(ma) = V$, $q(in) = V + B$, and $q(rc) = (V+B)(1-\gamma)$.[10] Note that if $k^i \neq k^{i'}$, the competing products are vertically differentiated. Hence, the model embodies both *vertical differences* in product quality and *horizontal differences* in consumer preference for product locations along the line (at 0 and 1).[11] Given the alternatives offered, a consumer buys whichever option delivers the greatest net utility as long as $u \geq 0$. We assume that a new cohort of consumers arrives in each period and, to focus on the role of product recall concerns under competition, we concentrate on the case in which the market is covered and both firms have positive demand.[12] Table 1 details the notation used throughout the analysis.

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[10] In the main model, we assume that consumers are homogeneous in their valuation for quality level. Section 6.1 relaxes this assumption and allows consumers to be heterogeneous in their willingness-to-pay (WTP) for product quality.

[11] Throughout the study, we use the term "differentiation" to refer to the *vertical difference* in product qualities. Note that the competing firms' products are, by default, *horizontally differentiated* per the demand structure in Equation (1).

[12] The associated constraints are satisfied in all subsequent analyses. The verifications are made explicit in the relevant proofs.

Table 1 Summary of Model Notation

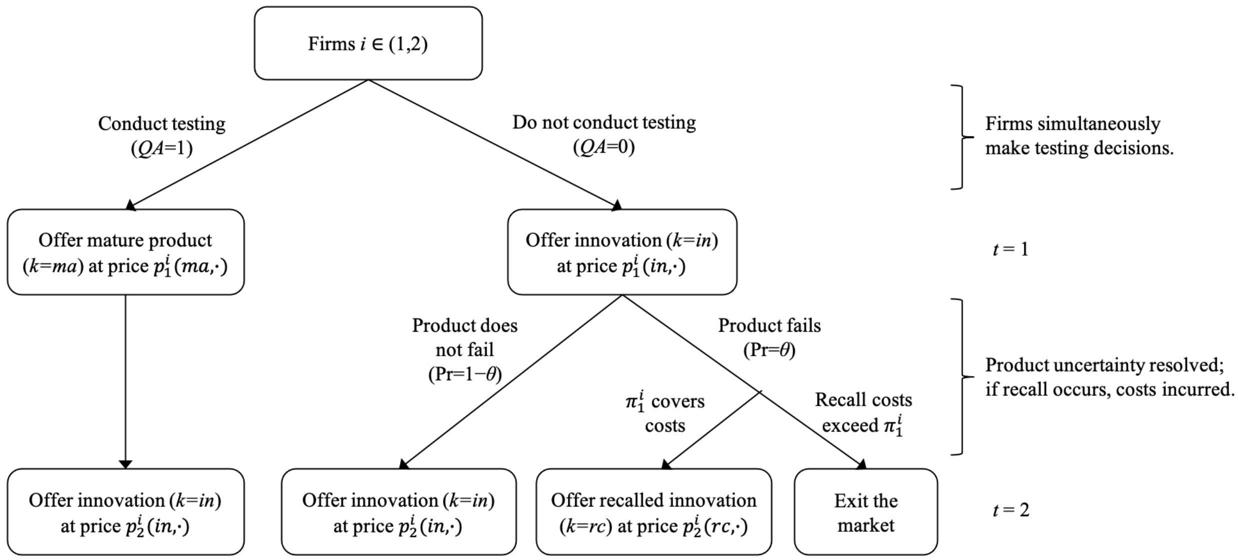
Notation	Definition
V	Quality level of mature product
B	Quality improvement of innovation
θ	Product failure probability (when testing is skipped)
ρ	Fixed cost of a recall
δ	Marginal cost of a recall
γ	Reputation damage
τ	Consumer sensitivity to horizontal disutility
Firm	
k_t^i	Product type offered by firm i in period t
$q(k_t^i)$	Quality level of product type k_t^i
p_t^i	Price for firm i in period t
d_t^i	Demand for firm i in period t
π_t^i	Profit for firm i in period t
QA^i	Firm i's testing decision
$\Pi^{QA^i,QA^{i'}}$	Firm i's total profit in subgame (QA^i,$QA^{i'}$)

We point out that consumers, as reflected in Equation (1), do not explicitly take into account the possibility of product failure when they observe an innovation offered at $t = 1$ (from which they could infer that the firm has forgone testing). Although one might interpret this as assuming "myopic" consumers, we believe that our approach is valid since, even if consumers draw such an inference, they also recognize that the firm's pecuniary penalty (Δ) will compensate them for the disutility caused by possible product failure. In Sections 6.2-6.3 we discuss relaxing this assumption in several ways.

3.4. Timing of the Game

Figure 1 summarizes the sequence of events in the multi-stage game. At the start of the game, firms simultaneously set their product testing strategies (QA). Given their decisions, each firm launches a product k_1^i ($= ma$ if testing and in if not testing) with a corresponding quality level $q(k_1^i)$ and sets the price p_1^i. By the end of $t = 1$, latent product uncertainties are resolved; recall costs are incurred (if applicable); and a firm that cannot fully cover the recall costs exits the market. At $t = 2$, active firms offer their innovations k_2^i ($= in$ if tested or if not tested and a recall did not occur; and rc if not tested and a recall occurred) and set prices p_2^i. The firms are risk-neutral and maximize expected payoffs.

Figure 1 Sequence of Events



4. Analysis

In this section, we analyze the strategic forces behind firms' quality assurance testing and innovation launch timing decisions. The analysis begins by solving for the optimal actions of a monopolist, which allows us to isolate a firm's incentives when competitive concerns are absent. The discussion then proceeds to characterize the equilibria in the duopoly case. All proofs are provided in Section A of the Online Appendix.

4.1. Monopoly Benchmark

Consider a monopolist, located at the center of the unit segment, making the product testing decision so as to maximize total profits.[13] The test decision and subsequent product recall outcome determine the monopolist's product offering, k_t^M, in each period (see the timeline in Figure 1). It is easy to verify that the monopolist's optimal price and profit are $p_t^M = \pi_t^M = q(k_t^M) - \tau/2$.

The following characterizes the monopolist's testing decision:

Proposition 1. *There exists a cutoff value θ^M such that if the product failure probability satisfies $\theta \geq \theta^M$, a monopolist conducts product testing and delays the launch of its innovation. If $\theta \leq \theta^M$, the monopolist forgoes product testing and launches its innovation immediately.*

[13] Qualitatively similar results hold if a monopolist is located at either endpoint of the unit segment; or if it is located at both endpoints, jointly maximizing the profits of two products. See Section A of the Online Appendix for details.

The cutoff value θ^M, which embodies the monopolist's considerations between forgoing vs. conducting quality assurance testing, is given by:

$$\theta^M \equiv \begin{cases} \frac{B}{(V+B)(\delta+\gamma)+\rho-\delta\tau/2} & \text{if } \rho \leq \rho^M, \\ \frac{B}{2(V+B-\tau/2)} & \text{if } \rho > \rho^M, \end{cases}$$

where ρ^M is the monopolist's threshold for the fixed cost of a recall ρ, above which it exits the market in the event of a product recall.

For a monopolist, the trade-off between conducting and forgoing quality assurance testing is straightforward. The firm considers the opportunity cost of not launching the innovation early ($=B$) relative to the negative consequences that could result from a recall. Such negative consequences involve a fraction of profits forfeited due to experiencing a recall ($=(V+B)(\delta+\gamma)+\rho-\delta\tau/2$), if the fixed cost of a recall is small ($\rho < \rho^M$) and the firm remains in the market; or the entire two-period profits ($=2(V+B-\tau/2)$), if the fixed cost of a recall is severe enough ($\rho \geq \rho^M$) to drive the firm out of business. Note that in the latter case, the cutoff θ^M no longer depends on the recall parameters ρ, δ and γ since the monopolist exits the market following a recall. Overall, if the probability of a product failure is low ($\theta < \theta^M$), the monopolist "takes on" the recall risk by forgoing testing and rushing to the market with its innovation (a *market pre-emption* effect). Otherwise, the monopolist prefers to "play it safe" and conducts testing to ensure a rigorously vetted innovation (a *recall avoidance* effect).

We make the following additional observation regarding the monopolist's cutoff value θ^M:

Corollary 1. *The cutoff value θ^M is increasing in the quality improvement B and consumer heterogeneity τ, decreasing in the mature product value V, and (weakly) decreasing in the recall costs ρ and δ, as well as the reputation damage γ.*

To understand why the cutoff θ^M is increasing in the consumer heterogeneity parameter τ, note that the marginal cost of a recall is proportional to first-period profits (i.e., $\delta \cdot \pi_1$), which are decreasing in τ for the monopolist (as $\pi_t^M = q(k_t^M) - \tau/2$). Hence, the amount necessary to reimburse consumers in the event of a recall decreases as τ goes up. The lower recall burden prompts taking on a greater risk of product failure θ, implying a higher threshold θ^M to test (in other words, the monopolist is less likely to conduct testing as τ increases).

The other relationships outlined in Corollary 1 are intuitive. Specifically, as the innovation's benefit B increases, the profit the monopolist can reap from an early launch grows; hence, the cutoff increases as B increases. The additional profit gain from an early launch is evaluated relative to the profit from selling the mature product of quality V, which is what the monopolist can earn when it delays the launch to conduct testing. Hence, the cutoff θ^M decreases as V increases. Furthermore, a rise in the negative consequences of a potential recall, represented by the recall costs ρ and δ, and the reputation damage γ, generally lowers the threshold that prompts testing.

4.2. Product Recalls and Competition

We now turn to the case of two competing firms. The analysis begins by examining the equilibrium prices and profits, which depend on the firms' testing decisions and product recall outcomes. As illustrated in Figure 1, the two firms offer products of different quality levels in the following cases: (1) At $t=1$, only one firm conducts testing and thus its mature product ($k_1^i = ma$) faces the rival's innovation ($k_1^{i'} = in$). (2) At $t=2$, only one firm's product experienced a recall and thus a recalled innovation ($k_2^i = rc$) faces a fail-proof innovation ($k_2^{i'} = in$). The following lemma characterizes the outcomes of the pricing subgame depending on the products offered.[14]

Lemma 1. *In the pricing subgame, the equilibrium prices and profits are as follows:*

- *If firm i markets its mature product ($k_1^i = ma$) while rival i' markets its innovation ($k_1^{i'} = in$),*

$$p_1^i(ma,in) = \frac{-B+3\tau}{3},\ \pi_1^i(ma,in) = \frac{(-B+3\tau)^2}{18\tau};\ p_1^{i'}(in,ma) = \frac{B+3\tau}{3},\ \pi_1^{i'}(in,ma) = \frac{(B+3\tau)^2}{18\tau}.$$

- *If firm i markets its recalled innovation ($k_2^i = rc$) while rival i' markets its innovation ($k_2^{i'} = in$),*

$$p_2^i(rc,in) = \frac{-(V+B)\gamma+3\tau}{3},\ \pi_2^i(rc,in) = \frac{(-(V+B)\gamma+3\tau)^2}{18\tau};\ p_2^{i'}(in,rc) = \frac{(V+B)\gamma+3\tau}{3},\ \pi_2^{i'}(in,rc) = \frac{((V+B)\gamma+3\tau)^2}{18\tau}.$$

- *Otherwise, the firms market products of identical quality, leading to $p_t^i = p_t^{i'} = \tau$, $\pi_t^i = \pi_t^{i'} = \frac{\tau}{2}$.*

A firm can thus attain one of five profit levels depending on the time period, the testing and launch decisions, and the probabilistic failure of the product. Two additional points are worth making here. First, when both firms forgo testing in the first period, their products can still be (vertically) differentiated in the second period if only one of the innovations experiences a recall. Second, when a firm launches its innovation early, in expectation it bears the direct cost of a product recall, $\theta \cdot \Delta = \theta \cdot (\rho + \delta \cdot \pi_1)$. If the

[14] The following constraint is imposed: $\frac{B}{3} < \tau < \frac{2V+B}{3}$ if $0 < \gamma < \frac{B}{V+B}$ or $\frac{(V+B)\gamma}{3} < \tau < \frac{(V+B)(2-\gamma)}{3}$ if $\frac{B}{V+B} < \gamma < 1$. The upper bound of the constraint ensures that the market is fully covered; the lower bound ensures that both firms have non-zero demand (i.e., no firm dominates the entire market).

rival launches its innovation early as well, intense competition will drive down prices and profits in the first period (i.e., $\pi_1^i(in, in) < \pi_1^i(in, ma)$), resulting in lower recall costs tied to dollar sales but also in less profits to cover the fixed recall costs.

We now characterize the equilibria of the entire game in terms of the decision to conduct quality assurance testing.

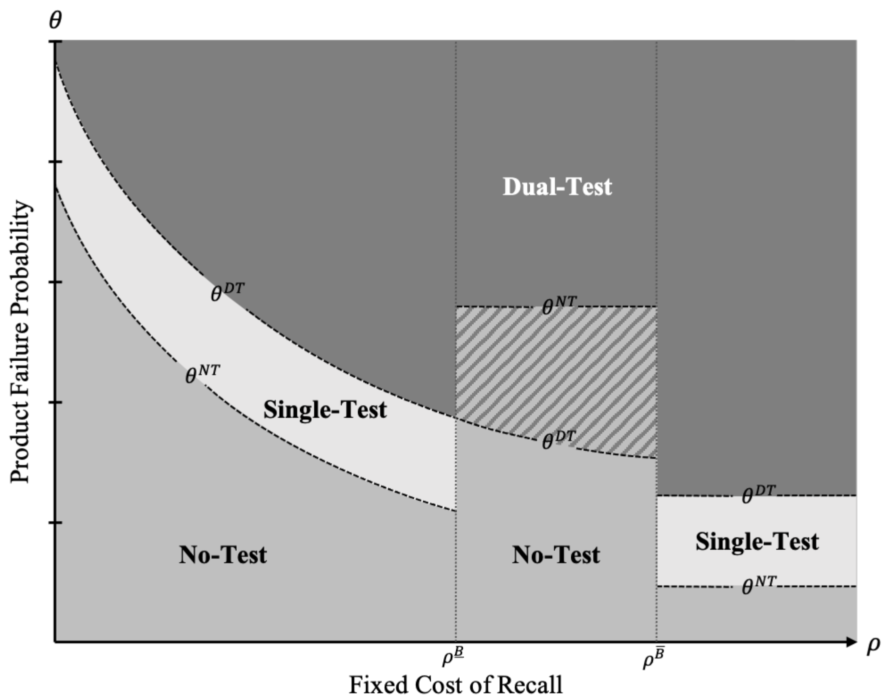
PROPOSITION 2. *In a duopoly, quality assurance testing decisions are determined by the following regions categorized by* θ^{NT} *and* θ^{DT}*:*

- *No-test equilibrium (symmetric): If* $\theta \leq \theta^{NT}$*, neither firm conducts testing and both rush to the market with their respective innovations.*
- *Single-test equilibrium (asymmetric): If* $\theta^{NT} < \theta < \theta^{DT}$*, only one firm conducts testing and the other rushes to the market with its innovation.*
- *Dual-test equilibrium (symmetric): If* $\theta \geq \theta^{DT}$*, both firms conduct testing and delay launching their innovations.*

Figure 2 provides a graphical illustration of the equilibrium regions described in Proposition 2 in the $\theta \leftrightarrow \rho$ parameter space. In general, we observe that: (1) when the failure probability is low, neither firm conducts testing and both rush to the market with their innovative product; (2) when the failure probability is intermediate, only one firm tends to conduct testing and the other rushes to the market; (3) otherwise, both firms conduct testing and delay the launch of their innovative product.

We are now ready to discuss the intuition behind each equilibrium region in greater depth and highlight a number of noteworthy comparative statics. Before diving into the details, note again the forces that come into play. As in the monopoly case, the trade-off between capturing greater demand in the first period (*market pre-emption*) and avoiding the risk of product failure (*recall avoidance*) remains. However, with competition there are several added considerations. The benefits of launching the innovation early (by forgoing testing) or of ensuring the introduction of a fail-proof product later (by testing) decrease if the rival firm takes an identical action—as the products marketed at $t=1$ will be of similar value and, depending on the recall outcomes, the same can be true at $t=2$. This competitive drawback pushes the firms to seek to vertically differentiate their offerings, which can be achieved by varying the timing of innovation launch (*differentiation incentive*). In contrast, if the potential disadvantages from lagging

Figure 2 Equilibrium Regions: Competing Firms' Decisions to Conduct or Forgo Testing



Notes. The dashed lines depict cutoff values θ^{DT} and θ^{NT}. The y-axis shows the product failure probability θ and the x-axis shows the fixed cost of a recall ρ. In the diagonal-striped region, multiple equilibria coexist (i.e., dual-test and no-test).

behind the competition in the product space outweigh the gains from differentiating, a firm that expects its rival to launch the innovation immediately will be motivated to follow suit and also launch at $t = 1$ (*anti-lag incentive*).

4.2.1. No-Test Equilibrium. In this region, both firms forgo testing and launch the innovation immediately. The relatively low probability of a product recall prompts both firms to rush to the market with their innovative products, in an effort to avoid lagging behind the competition (*anti-lag incentive*). By both rushing to the market, the firms achieve competitive level profits ($\tau/2$) in the first period. In contrast, if a firm deviates and conducts testing, it sacrifices profits in the first period by selling the mature product that is inferior (as $\pi_1^i(ma, in) < \tau/2$, per Lemma 1); despite guaranteeing a fail-proof innovation in the second period. Note also that the equilibrium is sustained even though upfront testing entails no costs.

Although one might intuitively expect that firms' tendency to forgo testing (and risk a recall) would decline as the negative consequences of a product recall become more severe, there is an interesting "jump" in the no-test equilibrium region as illustrated in Figure 2. Specifically, the region actually expands as the cost of a recall ρ increases above $\rho^{\underline{B}}$, the threshold for bankruptcy following a recall. We note the following result:

RESULT 1. *In an intermediate range of product failure probability θ, an increase in the fixed cost of a recall ρ above the threshold $\rho^{\underline{B}}$ can increase the region in which two competing firms release their innovations immediately.*

The result is interesting because it reveals that a stronger penalty for experiencing a product recall may, in fact, prompt both firms to rush to the market. The intuition for the emergence of this result is, surprisingly, linked to the implicit benefit of "betting" on the rival's product recall. In particular, if the rival's innovation "stumbles" and experiences a recall, the severity of associated costs can drive it out of business. Hence, by remaining the market's sole player, the firm is able to enjoy monopoly profits at $t = 2$. The prospects of such strong profits induce both firms to rush to the market.

One might wonder why in this case the single-test equilibrium region does not expand in the cost of a recall ρ. In other words, given its rival's decision to skip testing, why would the firm not want to deviate to testing—and remove the risk of its own product failing? To understand the reason, note the difference in profit levels: $\pi_1(in, ma) > \pi_1(in, in)$, per Lemma 1. This implies that the first-period profit of the rival, which launches its innovation immediately, is greater when it sells a superior quality innovation and faces a mature product (if the firm conducts testing) compared to when the two firms sell equally advanced innovations (if the firm also forgoes testing). By making more profits in the single-test scenario, the rival is less vulnerable to going out of business due to a recall than under the no-test scenario. If the cost ρ is intermediate ($\rho^{\underline{B}} < \rho < \rho^{\bar{B}}$), the rival who launches early and experiences a recall will go bankrupt in the no-test scenario, but has sufficient resources to *withstand* the recall in the single-test scenario. Therefore, it is the negative impact on first-period prices and profits brought about by matching the rival's early launch decision that facilitates the "betting exchange" for the firms—as it creates an attractive winner-take-all situation in the second period should the rival's product falter. This makes it worthwhile for the firm to risk its own product failure (in which case it would make 0 profits). Thus, only the no-test equilibrium region expands as fixed recall costs rise above $\rho^{\underline{B}}$. Note that as ρ increases beyond $\rho^{\bar{B}}$, the no-test equilibrium region narrows since the rival (with an early launch) goes bankrupt even in the single-test scenario.

A related aspect of this parameter region pertains to how firms' profits depend on the product failure probability. Notably, profits in the no-test equilibrium increase and then decrease in the failure probability θ when $\rho > \rho^{\underline{B}}$. The intuition comes from the probabilistic occurrence of recalls. For the firm to enjoy monopoly-level profits at $t = 2$ per Result 1, the rival's innovation should experience a recall (with probability θ) while its own innovation should not (with probability $1 - \theta$). Combining these product failure scenarios, the firm attains monopoly profits with probability $\theta(1-\theta)$. This quadratic relationship between the recall probability and the attainment of monopoly profits in the second-period gives rise to the non-monotonicity. Said differently, for the likelihood of enjoying monopoly profits to be non-negligible, the probability of product failure should neither be too low nor too high.

Another interesting aspect of this equilibrium is how the horizontal demand structure influences firms' willingness to conduct testing:

Result 2. *The size of the no-test equilibrium region exhibits a non-monotonic relationship with consumer heterogeneity τ; initially expanding and subsequently shrinking with τ.*

That is, both firms are more likely to forgo testing and launch the innovation immediately if consumers' sensitivity to horizontal mismatch is moderate (τ is intermediate); while one of the firms is more likely to deviate and conduct testing if consumer preferences are either relatively homogeneous (τ is small) or very heterogeneous (τ is large). The intuition is as follows. When the value of τ is small, the market is very competitive in the horizontal dimension and firms are better off avoiding intense rivalry by diverging in their testing decisions to distinguish their offerings on the vertical dimension (i.e., one firm launches the innovation while the other markets its mature product). Initially as τ increases, consumers become more heterogeneous in their horizontal preferences and the benefits of vertical product differentiation erode, providing support for the no-test equilibrium. However, as τ grows further, prices and profits grow in a competitive market. Hence, the amount of money necessary to reimburse consumers in the event of a recall also increases in proportion. Eventually, it becomes difficult to sustain the no-test equilibrium and one of the firms deviates, leading to the single-test equilibrium. We point out that, if only the differentiation incentive is considered without product recall considerations (as in conventional launch-timing games), the equilibrium region in which firms rush to the market would monotonically increase in τ.

4.2.2. Single-Test Equilibrium. In this equilibrium, one firm rushes to the market, seeking to enjoy the spoils from being the sole innovator in the first period (*market pre-emption*), while taking on the risk of selling a faulty product. The rival, however, decides to be more cautious and thoroughly tests its new product to eliminate the possibility of a recall (*recall avoidance*). The uncorrelated actions also allow the firms to offer distinct products across time (*differentiation incentive*)—certainly in the first period $\{in, ma\}$ and possibly in the second period if the firm that forgoes testing incurs a recall $\{rc, in\}$.

A noteworthy aspect of this equilibrium is that it can be sustained even when the failure probability θ is relatively high. More formally, a firm may release its untested innovation immediately even as $\theta \to 1$, provided the financial consequences of a recall are minimal. This implies that a firm, knowing that its innovation would very likely fail and be recalled, may nonetheless rush to the market.[15] The intuition is as follows. If the pecuniary costs associated with a recall (ρ and δ) are modest (see Figure 2 top left region) and the benefits from pre-empting the market (B) are large, by forgoing testing and launching its innovation early a firm attempts to take full advantage of its superior product in the first period, while accepting the consequences associated with (an almost certain) product recall. The other firm, in contrast, conducts testing to benefit from a superior fail-proof innovation in the second period (as its rival will very likely market a recalled product).

We note that in this equilibrium, one firm prioritizes the exclusive benefits of an early launch in the first period, while the other relies on the expected advantage of a robust innovation in the second period. The relative profitability each firm enjoys under the asymmetric outcome depends on the strength of these countervailing considerations. When the innovation benefit B is relatively high (i.e., there is a strong market pre-emption effect), the overall profits of the firm that forgoes testing are greater than its rival's. By contrast, the firm that conducts testing enjoys greater overall profits when the consequences of a recall—failure probability θ, recall costs ρ and δ, and reputation damage γ—are high (i.e., the recall avoidance effect along with a differentiation incentive dominate). From an empirical standpoint, the asymmetric equilibrium suggests that, under the appropriate conditions, heterogeneity in firm behavior with respect to quality assurance testing and the timing of new product introductions will be observed.

[15] A real-world example is launching a minimum viable product (MVP), i.e., a premature, working version of the innovation, which firms release in an attempt to better understand the market and pass on the testing activities to consumers; thus collecting market feedback about product defects and shortcomings.

4.2.3. Dual-Test Equilibrium. When a recall is relatively likely and the costs associated with it are non-negligible, an equilibrium in which both firms conduct testing is sustained. The desire to avoid a costly recall drives both firms to be prudent, even though a deviation by one of the firms to skip testing would yield healthy profits to the deviating firm in the first period and probabilistic product differentiation in the second period.

The dual-test equilibrium region is bounded from below by the cutoff θ^{DT} (see Figure 2). This cutoff represents the level of failure probability θ governing the firm's decision of whether to test given its rival's decision to test. If $\theta < \theta^{DT}$, the *market pre-emption* incentive kicks in and the firm rushes to the market (i.e., single-test equilibrium). Conversely, if $\theta > \theta^{DT}$, the *recall avoidance* is large and the firm is also better off testing (i.e., dual-test equilibrium). The following characterizes the comparative statics of the cutoff θ^{DT}:

Corollary 2. *The cutoff value θ^{DT} is increasing in the quality improvement B, decreasing in the consumer heterogeneity τ, and (weakly) decreasing in the mature product value V, the recall costs ρ and δ, as well as the reputation damage γ.*

An implication of Corollary 2 is that the comparative static for θ^{DT} w.r.t. τ is opposite in direction to that of the monopoly cutoff value θ^{M}, which is increasing in τ (per Corollary 1). That is, as consumer heterogeneity τ becomes stronger, the threshold for the recall probability θ to trigger a monopolist to conduct testing goes up (i.e., a monopolist is less inclined to test); while in a duopoly this threshold goes down (i.e., both firms are more inclined to test). The result arises because consumer heterogeneity affects both the profits and the recall costs. For a monopolist, consumer heterogeneity τ may be viewed as an expense to reach heterogeneous consumers (since greater consumer sensitivity to product mismatch induces the monopolist to lower its price), thus limiting the attainable profits. In a competitive environment, however, τ plays a horizontal differentiation role; thus τ is positively reflected in the firms' profit expressions (per Lemma 1). Now, if a firm rushes to the market and experiences a recall, it incurs the marginal cost $\delta \cdot \pi_1$, which is a function of τ. In a monopoly, since price and profits are negatively related to τ, an increase in τ mitigates the potential cost of a recall when launching the innovation immediately; hence a monopolist is more inclined to forgo testing as τ rises. In a duopoly, however, firms' profits are positively related to τ, which, in turn, increases the costs to reimburse consumers following a recall.

Moreover, a larger τ reduces the relative gains from market pre-emption and differentiation on the vertical dimension. Consequently, both firms are prompted to conduct testing as consumer heterogeneity in horizontal preferences strengthens.

Having discussed all three equilibrium regions, we now examine how the various incentives under competition may lead firms into a sub-ideal situation. We state the following result.

Result 3. *Firms' expected profits in the no-test equilibrium may be lower than the expected profits had they both been able to commit to testing.*

Hence, the classic prisoner's dilemma outcome emerges because of product recall pressures. The intuition is as follows. Facing a rival that plans to delay the launch and test, a firm has a strong incentive to launch its innovation early and enjoy the benefits of offering a superior product (*differentiation incentive*). This incentive grows as the innovative benefits B become stronger (*market pre-emption*). However, given such a decision by the firm, the rival's profits drop significantly (and in proportion to B), since it markets an inferior product in the first period and potentially a similarly valued innovation in the second. Hence, the rival is also inclined to skip testing so as to avoid being a laggard that is at a disadvantage (*anti-lag incentive*). As a result, competitive forces drive both firms to risk the possible consequences of a recall without capitalizing on the innovative benefits, whereas they would have been better off by first testing and only launching their robust innovations in the later period.

To summarize, we have characterized the various equilibria in terms of firms' actions. A variety of underlying factors, including the quality of the products, the fixed and variable costs of a recall, and the reputation damage to a recalled innovation, were shown to play a role in and give rise to three equilibrium regions. When the probability and consequences of a product recall are non-negligible, the *recall avoidance* force dominates and the equilibrium in which both firms conduct testing and delay launching their innovations holds. However, when the consequences are less substantial and when the benefits of the innovation are sufficiently valued, the single-test equilibrium emerges. In this equilibrium, one firm launches its innovation immediately to capitalize on early demand (*market pre-emption*) while the other conducts testing to avert a potential mishap associated with a product recall (*recall avoidance*). Such asymmetry in behavior is reinforced by the *differentiation incentive*, whereby competing firms attempt via the testing decision to distinguish their product offerings and thus mitigate intense competition.

Lastly, when the consequences of falling behind the competition in the product space are large (*anti-lag incentive*), an equilibrium in which both firms forgo testing is sustained. Interestingly, the lower profit levels resulting from intense competition in the first period may induce both firms to launch early, even though the fixed costs of handling a recall go up. The mechanism behind this behavior is that a reduced profit-level raises the prospects of going bankrupt in the event of a recall—which, if it (probabilistically) occurs only to the rival, offers the firm an opportunity to enjoy monopoly-level profits in the future. Furthermore, the size of the no-test equilibrium region is non-monotonic in consumers' sensitivity to horizontal mismatch: for high or low values of the heterogeneity parameter, a firm facing a rival that rushes to market is inclined to conduct testing; whereas for intermediate values of this parameter, the firm rushes to market as well.

5. Product Recalls and the Decision to Innovate

The main model analyzed firms' testing decisions (QA) assuming they had already engaged in product development. Thus, both firms were exogenously endowed with an innovation at the start of the game. We now ease this assumption and consider the case in which the firms first need to determine their new product development strategies, that is, whether to innovate in the first place. This allows us to examine how factoring in the possibility of product failure and recall affects firms' willingness to undertake R&D effort. Intuitively, one might expect that product recalls (or the need to delay a launch to assure a product is defect-free) unequivocally diminish the incentives to innovate. However, we show that this intuition does not always hold and characterize conditions under which firms are in fact more motivated to engage in innovative effort as the likelihood of a recall increases.

Suppose that firms $i \in \{1, 2\}$ determine their new product development strategies at $t = 0$ (i.e., preceding the launch/test period at $t = 1$). More specifically, let them face a decision about whether to invest in R&D, indexed by $RD \in \{0, 1\}$, where 1 denotes choosing to invest and 0 otherwise. When a firm decides to invest ($RD = 1$), it incurs a fixed R&D cost denoted by η and is guaranteed successful development of an innovation before $t = 1$. Note that this innovation still bears a probability of failure $\theta \in (0, 1)$ prior to undergoing quality assurance testing. By contrast, if a firm decides not to invest in R&D ($RD = 0$), it does not incur any development costs and markets its mature product throughout the game.

Based on their investment decisions at $t = 0$, the firms then market their products over two periods $t = \{1, 2\}$. When neither firm decides to innovate, the firms are "stuck" with their mature products of value V and the resulting subgame profits are fixed (i.e., there is no role for product testing and no recalls). When both firms invest in R&D and develop innovations, they are, in effect, in the same situation as in the basic setup at $t = 1$. Hence, the analysis of their test decisions and profit structures carries over from the duopoly case analyzed in Section 4.2.

When only one firm invests in R&D and innovates, it alone has to make the product testing decision at $t = 1$. However, the sole innovator's decision in a duopoly is different from that of a monopolist with an innovation (per Section 4.1) since the sole innovator faces competition from the non-innovating rival's mature product. To fully characterize this scenario, we need to consider a new type of competitive subgame that emerges if the sole innovator decides not to test: At $t = 2$, if its innovation suffers a recall ($k = rc$), it faces the mature product ($k = ma$) of the non-innovating rival.[16] Under such competition, when the reputation damage is small (large), the recalled innovation is superior (inferior) to the mature product.

Having discussed the details of the underlying subgame, we now characterize the equilibria of the entire game in terms of the decision to invest in R&D.

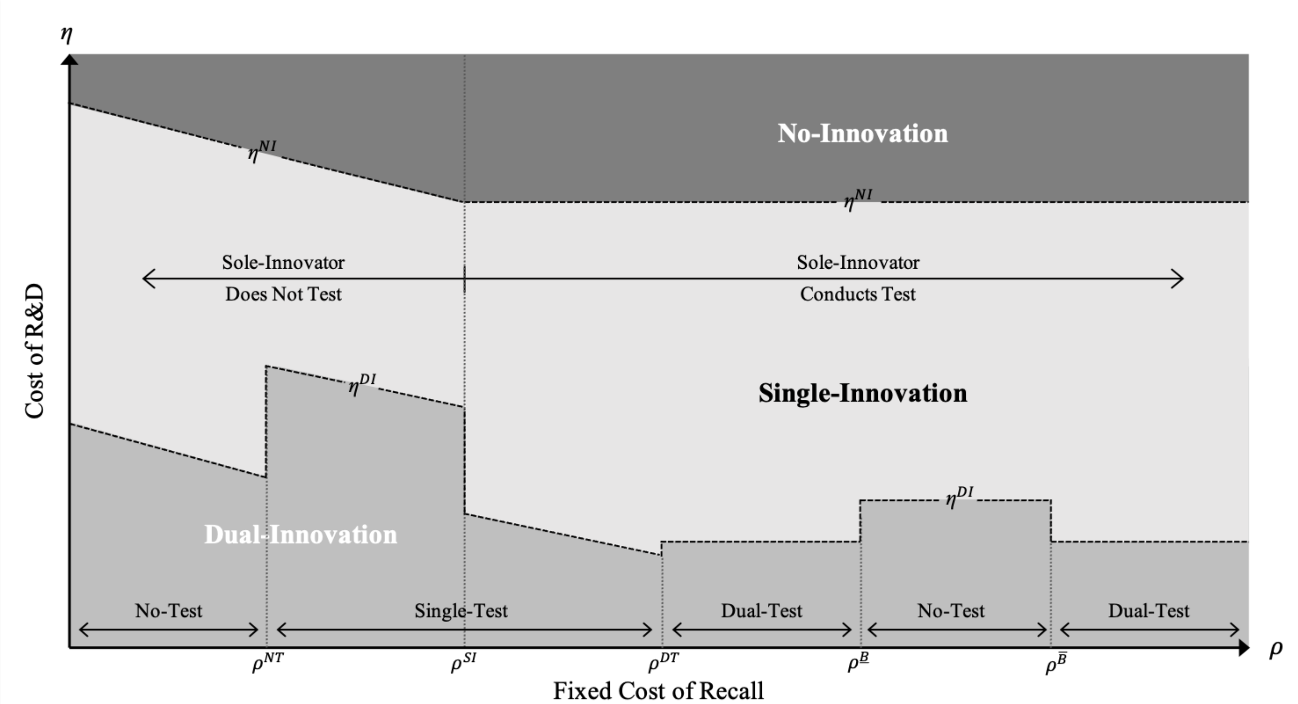
PROPOSITION 3. *There exist R&D cost cutoff values η^{NI} and η^{DI}, as a function of the recall parameters θ, ρ, δ, and γ, such that the following equilibria of the game exist:*

- *No-innovation equilibrium: If $\eta \geq \eta^{NI}$, neither firm invests in R&D.*
- *Single-innovation equilibrium: If $\eta^{DI} < \eta < \eta^{NI}$, only one firm invests in R&D.*
- *Dual-innovation equilibrium: If $\eta \leq \eta^{DI}$, both firms invest in R&D.*

To understand the findings laid out in the proposition, note that the firms face a trade-off: R&D effort is costly but results in an innovation that is of higher value than the mature product. However, this benefit from R&D decreases if the rival firm invests in R&D as well because the innovative products introduced are expected to be less differentiated in the subsequent periods. If the cost of R&D is prohibitively high, neither firm is willing to invest in development because, even with a product advantage at $t = 1$ (and potentially at $t = 2$), the expected profits when facing a competitor with a mature product of quality V are not adequate to cover the costs. At an intermediate R&D cost region, we get the result whereby one

[16] Detailed derivations and outcomes of this pricing subgame are shown in the Online Appendix, as part of the proof of Proposition 3. The following constraint is imposed (in addition to Footnote 14): $\frac{B-(V+B)\gamma}{3} < \tau < \frac{V+(V+B)(1-\gamma)}{3}$ if $0 < \gamma < \frac{B}{V+B}$ or $\frac{(V+B)\gamma-B}{3} < \tau < \frac{V+(V+B)(1-\gamma)}{3}$ if $\frac{B}{V+B} < \gamma < 1$.

Figure 3 Equilibrium Regions: Innovation Decision



Notes. The dashed lines depict cutoff values η^{NI} and η^{DI}. The y-axis shows cost of R&D η and the x-axis shows the fixed cost of a recall ρ.

firm engages in R&D to possess the innovation at $t = 1$, while its rival stays content with the mature product. This outcome is driven by the fact that one firm's expected profits from innovating are adequate to cover the R&D cost by giving it an advantage over its rival. However, when both firms conduct R&D, the dampening force of competition prevents the firms from being able to recover their R&D expenses. Lastly, if the cost of R&D is low, both firms decide to innovate.

Figure 3 illustrates the equilibrium regions emerging in the $\eta \leftrightarrow \rho$ space. Notice the pair of decisions in play: (1) the decision to innovate and (2) the subsequent decision to conduct testing (if the firm innovated). Two observations are noteworthy from the figure. First, the no-innovation cutoff η^{NI} remains constant beyond ρ^{SI}, the threshold for ρ above which a sole innovator conducts quality assurance testing. This occurs because testing removes the risk of product failure, and thus the cost of a recall no longer plays a role in determining equilibrium outcomes.

Second, the dual-innovation cutoff η^{DI} exhibits a number of "jumps" as the fixed cost of recall ρ increases. Importantly, these jumps demonstrate that a higher recall cost may actually increase the likelihood of two competing firms investing in R&D. Table 2 summarizes the intuition behind each of the jumps. To better understand the table, note that the dual-innovation cutoff η^{DI} (which determines

Table 2 Intuition Behind the Jumps in the Dual-Innovation Cutoff η^{DI}

Threshold	Outcome of the testing subgame (assuming the rival innovates)	Effect on innovation
ρ^{NT}	If the focal firm innovates as well: The ensuing subgame shifts from no-test to single-test. This results in temporal differentiation, increasing the benefits of innovating.	More likely for both firms to innovate.
ρ^{SI}	If the focal firm does not innovate: The innovating rival in the ensuing subgame shifts from not testing to testing. The rival's delayed launch alleviates the disadvantages of not innovating for the focal firm.	Less likely for both firms to innovate.
ρ^{DT}	If the focal firm innovates as well: The ensuing subgame shifts from single-test to dual-test, resolving the product recall concerns of innovating.	More likely for both firms to innovate.
$\rho^{\underline{B}}$ (until $\rho^{\bar{B}}$)	If the focal firm innovates as well: The ensuing subgame shifts from dual-test to no-test, creating conditions for monopoly-level profits if the rival fails.	More likely for both firms to innovate.

Notes. See Section B.8 of the Online Appendix for additional observations on how the dual-innovation cutoff might change as a function of ρ.

the split between the dual-innovation and the single-innovation regions) is governed by the incentives of a firm facing a rival that innovates. If the incentives to innovate become stronger, the dual-innovation equilibrium expands; otherwise, the single-innovation equilibrium expands. Yet the payoffs from investing vs. not investing in R&D also depend on the testing subgame following the innovation decisions.

We now seek to understand more explicitly how the probability of a product recall affects a firm's willingness to innovate. One might intuitively surmise that firms' willingness to invest in R&D declines as the probability of a product failure rises, since this reduces the expected gains from the innovative product by either prompting the firm to delay the launch (to conduct testing) or by increasing the risk of incurring recall costs (if testing is skipped). This logic certainly holds for a monopolist. However, as the next result shows, under competition firms' willingness to engage in R&D can increase as the probability of a product recall rises.

Result 4. *A higher product failure probability θ can increase the likelihood of both firms innovating.*

This result is surprising because it reveals that there exist conditions under which a greater product failure probability leads both firms to be more inclined to invest in R&D. The result is supported for two different scenarios as explained below, which reveals a fundamental interaction between the decision to innovate and the subsequent decision to conduct quality assurance testing.

The first scenario in which Result 4 holds arises when the testing subgame entails only one firm choosing to test (i.e., the single-test equilibrium). The intuition is as follows. A firm facing a rival that decides to innovate is confronted with a dilemma regarding whether to incur the R&D investment and innovate as well vs. stick to the mature product and be at a disadvantage in the product space (while saving on R&D expenses). If the firm decides to innovate and is the one that conducts testing, it gains a large profit at $t=2$ ($\pi_2(in, rc)$) when the rival, which skipped testing, stumbles due to a product recall. Yet even if the firm is the one to forgo testing, it earns healthy profits in the first period ($\pi_1(in, ma)$) and positive second period profits (even following a recall, as $\pi_2(rc, in) > 0$). Combining the two eventualities, and recognizing that the testing subgame is asymmetric, the expected profits of innovating increase in the product failure probability θ because this offers greater prospects of selling vertically differentiated products at $t=2$. Conversely, if the firm decides not to invest in R&D, its profits are invariant to the failure probability θ as the sole-innovating rival conducts testing.

The second scenario in which Result 4 holds arises when the testing subgame entails neither firm choosing to test (i.e., the no-test equilibrium) and a high enough fixed cost of handling a recall (so that a firm experiencing a recall exits the market). The intuition here follows from the non-monotonicity of firm profits discussed in connection with Result 1. When both firms launch their innovations early, a higher recall probability initially increases expected profits because, with probability $\theta(1-\theta)$, the rival's innovation will experience a recall while one's own innovation will not, in which case the firm will enjoy monopoly profits.[17] Because the expected gains from the innovation rise, the firm is prompted to innovate even for greater R&D costs; rather than settle for the limited profits from a mature product. Consequently, under the above two scenarios, as the probability of a recall increases the expected gains from innovating grow and, all else equal, both firms prefer to innovate; effectively expanding the region of the dual-innovation equilibrium. In some sense, greater recall concerns may actually spur rather than hinder innovation.

6. Extensions and Robustness Checks

The analysis thus far has focused on understanding the core mechanisms behind competing firms' new product testing and R&D investment decisions when they face the risk of a product recall. In this

[17] From the discussion of Result 1 we know that a higher recall probability (θ) simultaneously increases concerns over the focal firm's own product failure (in which case it earns zero profits). For small-to-intermediate values of θ, the provision of monopoly profits dominates and governs the overall (combined) expected profits; as θ grows high, however, the own product recall concerns eventually dominate and firms are less likely to innovate.

section, we examine several additional issues relevant for firms' behavior when they contemplate the trade-offs inherent in launching hitherto untested innovations into the marketplace. We also relax a few key assumptions made in the main model with a view toward establishing the robustness of our findings and increasing their range of applicability. Details of the analysis for all these extensions are provided in Section B of the Online Appendix.

6.1. Consumer Heterogeneity in Willingness-To-Pay (WTP) for Innovations

The main model setting presented in Section 3 assumes that consumers are heterogeneous in their preference for each brand (i.e., a horizontal demand structure). A different dimension of heterogeneity can be captured by varying consumers' valuation for the benefits of the innovation (vs. the mature product). To evaluate how such differences in market structure affect firms' testing decisions, we examine a modification in which the market is composed of a unit mass of consumers who are heterogeneous in their WTP for product quality (i.e., a vertical demand structure).

The vertical demand structure has several implications for firms' profits and thus actions. If competing firms offer products of equal quality, Bertrand price competition (Tirole 1988) ensues, which drives prices and profits to zero. This implies that a firm prices above zero only when the product it offers is distinct from its rival's. Hence, the *differentiation incentive* becomes significantly stronger under the vertical setting. This further pushes firms to vary the timing of their innovation launch, and, as a result, the single-test equilibrium region exists over a wider range of parameter values than in the horizontal demand structure. Notwithstanding, the analysis reveals that the majority of our results under the main setup (excluding those specifically related to the horizontal preference parameter τ) continue to hold qualitatively.

6.1.1. Product Selection and Shelving an Innovation. An interesting result obtained in the vertical demand structure described above relates to firms' product selection. In the main model, we assumed that firms were inclined to offer their innovations unless they chose to conduct testing (in which case they would offer the mature product at $t = 1$ and their thoroughly vetted innovation at $t = 2$). Hence, a firm that launched its innovation early was not allowed to "go back" and offer the (now legacy) mature product in the subsequent period. In other words, the firms could not select which product to offer at $t = 2$, even if they "technically" possessed a portfolio of products $\{\{ma, in\}, \{ma, rc\}\}$. Although this assumption makes sense, as in reality firms rarely revert to offering legacy products that have been phased out, the restriction could be seen as limiting since a firm may improve its profits by having the opportunity to select from a broader set of alternatives.

Under the horizontal demand structure, this restriction is of little strategic concern because firms are always better off launching their most valued product in the eyes of consumers. Under the vertical setting, however, launching the highest-quality product is not always ideal. As a result, we find that a firm may choose to shelve its innovation and market its mature product despite conducting product testing and, under some conditions, despite facing the rival's recalled product. The intuition is as follows. A firm's decision regarding which product to offer from its portfolio is governed in large part by the desire to avoid head-to-head competition. Since consumers are heterogeneous in their WTP for product quality, the firm can capture demand while charging a positive price (and thus generate a profit) even if the mature product it markets is of lower quality than the rival's.

6.2. Consumers Consider the Recall Probability of an Innovation Marketed Early

In our model, the per-revenue cost of a recall δ can be linked to forward-looking consumer behavior, since buyers can rest assured that they will be compensated for any expected loss resulting from a recall. In particular, as $\delta \to 1$, consumers will be fully compensated and incur only a minimal expected net loss, if any, as a result of a recall. However, when $\delta \to 0$, consumers can be viewed as "myopic." To reconcile this concern, we allowed firms' testing decisions to be common knowledge for all players. That is, consumers strategically consider the probabilistic failure of an innovation offered at $t = 1$ as well as the potential for the firm's bankruptcy as a result. More specifically, define $u^i = \mathrm{E}_{\theta,\delta}[q(k_t^i) - p_t^i] - \tau(i - 1 + (3 - 2i)x)$ for $i \in \{1, 2\}$, where

$$\mathrm{E}_{\theta,\delta}[q(k_t^i) - p_t^i] = \begin{cases} (1 - \theta \cdot \mathbb{I}_{k_1^i = in})q(k_t^i) - (1 - \delta\theta \cdot \mathbb{I}_{k_1^i = in})p_t^i & \text{if } \rho \le \rho^i, \\ (1 - \theta \cdot \mathbb{I}_{k_1^i = in})q(k_t^i) - p_t^i & \text{if } \rho > \rho^i. \end{cases}$$

Here, $\mathbb{I}_{k_1^i = in}$ is an indicator function equal to 1 if $k_1^i = in$ and 0 otherwise, and ρ^i is firm i's threshold for bankruptcy following a recall. Hence, upon observing an early launch of the innovation, consumers consider both (1) the possible loss in product value they must bear if the product malfunctions and (2) the associated monetary compensation they can retrieve in the event of a recall, which is in proportion to δ if the firm remains in the market and zero if it goes bankrupt. We find that, when the innovative benefits outweigh the failure risks ($B/(V+B) > \theta$), our results are qualitatively unaffected because consumers' expected utility from the innovation, despite the risk of its failure, is still greater than their expected utility from the mature product. When product risk is overwhelming ($B/(V+B) < \theta$), the risk of new product failure renders its expected utility lower, but the differentiation incentive still holds. Thus, although some comparative statics need to be qualified, we can still support all our major conclusions in certain regions of the parameter space.

6.3. A Segment of Consumers Avoids the Purchase of a Risky Innovation

The main model assumes the market size for the products is fixed and equal across the two periods (with the cohort size in each period normalized to 1). In practice, however, some consumers may be risk-averse and postpone their purchase of an innovation until it is deemed fully safe and reliable. Hence, we examine a modification in which there exists a segment of consumers who avoid the purchase of a risky innovation and let the market size vary accordingly across periods. More specifically, define a risk-averse segment of size α as those consumers who desire to possess an innovation, but only consider purchasing when it is deemed fully safe and reliable (i.e., at $t=2$). Thus, the total market size is $1-\alpha$ in the first period and $1+\alpha$ in the second period. We find that our key results continue to hold under this alternative setting. Furthermore, although in most cases a larger α leads to more testing by the firms (as this diminishes the benefits of an early launch), the analysis reveals an exception in which a larger α may lead to less testing. Specifically, this applies within the region $\rho^{\underline{B}} < \rho < \rho^{\bar{B}}$, in which one of the firms exits the market following a recall and the remaining firm enjoys monopoly profits. In this case, a larger α increases the level of monopoly profits at $t=2$, which provides an incentive for firms to rush to the market with their innovations (to create conditions for a rival to go bankrupt if its innovation is recalled), even as more consumers delay purchase.

6.4. Asymmetric Recall Probabilities

In the main model, firms possess an identical, industry-wide product failure probability θ. In reality, firms in the same industry may have different product failure rates. Hence, we examine a modified setting that accommodates this possibility. In particular, let one firm's new product failure probability be θ and the other firm's $\beta \cdot \theta$. Note that the latter firm's likelihood of a recall is lower than that of the former's if $0 < \beta < 1$ and higher otherwise. We find that our main model results continue to hold under this alternative setup. Notwithstanding, several new comparative statics emerge with respect to the parameter β. Specifically, when $0 < \beta < 1$, the dual-test region expands in β, whereas the no-test region is unaffected; conversely, when $1 < \beta < 1/\theta$, the no-test region shrinks in β, whereas the dual-test region is invariant to β. To understand the intuition, note that the decision for both firms to conduct testing is now governed by the firm with a lower failure rate—if the consequences of a recall are severe enough to trigger it to test, the rival with a higher failure rate would certainly do the same. Similarly, the decision for both firms to forgo testing is governed by the firm with a higher failure rate—if the benefits of early launch are large enough for it to forgo testing, the rival with a lower failure rate would certainly rush to the market as well.

6.5. The Cost of a Recall Depends on the Number of Units Demanded

In the event of a product recall, firms in our model incur a direct cost that, in part, depends on their revenues generated in the first period. This implies that the penalty parameter δ reflects the fraction of revenue the firm needs to compensate customers for the defect. This premise was justified in Section 3.2 using examples of scenarios in which the assumption is realistic. However, it is conceivable that, in some settings, the marginal cost associated with a recall is better linked to the units sold at $t = 1$ (i.e., $\hat{\Delta} = \rho + \hat{\delta} \cdot d_1$) than to the revenue generated. We find that all our results continue to hold qualitatively in this alternative setting. We further point out that this alternative assumption can drive up the price of an innovation introduced at $t = 1$. To understand why, note that the firm rushing to the market now has an incentive to reduce its first-period demand, since lower demand means fewer units sold and hence a smaller penalty incurred in the event of a recall. Thus, the firm raises the price of a risky innovation in proportion to the per-unit monetary cost, $\hat{\delta}$, and failure probability, θ, thereby transferring a portion of the potential cost of a recall onto customers.

7. Conclusion

The recall of a new product, when it occurs, can pose a serious threat to a firm's profitability and, in some scenarios, to its very existence. A major business dilemma firms face once the new product development phase has been completed is whether to conduct time-consuming quality assurance testing that would prevent such a debacle from occurring vs. launch the innovation immediately and seize early market demand. Navigating this dilemma involves accounting not only for the possible consequences of a product recall over time but also for competitive pressures in the marketplace.

In this study, we analyzed the strategic interaction between competing firms and examined the factors that influence their behavior when confronted with the testing vs. speeding to market conundrum. Two firms, both having developed an innovation, make quality assurance testing and launch-timing decisions under the risk that their products may fail. By conducting the test, the firm resolves recall concerns but sacrifices profits by having to sell its legacy product in the first period. In contrast, by forgoing testing and immediately introducing its innovation, the firm can enjoy greater profits from selling a more-advanced product. Such a course of action, however, involves the risk of a product recall, which entails costs to reimburse, fix or replace the new product for all consumers who had purchased it and causes future damage to the product's reputation as well.

Our analysis uncovers the primary forces that come into play in this setting: a desire to avoid the detrimental costs associated with a product recall; an impetus to cash in on the value consumers place on the innovative benefits; an incentive to avoid lagging behind the competition on the vertical dimension; and a motivation to refrain from taking an action that is identical to the rival's as this intensifies competition. The net impact of these effects determines the equilibria of the game, which can be symmetric (no-test or dual-test equilibria) or asymmetric (single-test equilibrium).

Several important managerial implications emanate from our findings. First, unless the costs associated with a recall are expected to be high, a firm should worry less about offering a flawless product and take advantage of the benefits of introducing its innovation sooner rather than later. Moreover, if a firm expects its primary rival to undertake time-consuming quality assurance testing, this further reinforces the advisability of forgoing such testing and betting on the innovation.

Second, even when recall costs are high and the primary rival is expected to launch its innovation early, the best course of action may not always be to spend extra time to secure a fail-proof product (while selling an inferior product in the current period). Specifically, in industries where the probability of a product failure is moderate, yet if a recall does occur the reimbursement expenses are substantial (with firms exiting the market as a result), a better move may be to rush to market as well. Such behavior sparks intense competition in the early period, leading to lower revenues and rendering the firms vulnerable to bankruptcy in the event of a recall. However, if only the rival falters, the rewards of market exclusivity from the absence of competition in the subsequent period (a “winner take all” eventuality) provide a strong impetus to launch early. Furthermore, the desire to rush to market is reinforced when consumer heterogeneity is intermediate. Conversely, a firm may be better off testing and delaying the debut of its innovation when consumer preferences are homogeneous (since a delayed launch helps avoid intense rivalry) or when they are highly heterogeneous (since in that case a recall would involve a large amount of compensation).

Third, in situations whereby an innovation offers significant consumer benefits over its preceding version, the fear of lagging behind a rival may cause all firms to rush their new products to market. However, this may prove detrimental, as the resulting intense competition renders profits lower, while at the same time exposing the firms and consumers to the possibility of experiencing a product failure. Profits and consumer welfare would be higher had the firms been able to commit to testing their innovations (i.e., a prisoner’s dilemma situation occurs). In such industries, regulation and 3rd-party supervision, which mandates firms to ensure the safety and functionality of their innovations prior to release, may avail firms and consumers alike.

Fourth, regarding the decision of whether to innovate at the outset, we find that the recommended course of action depends on the degree of product malfunction uncertainty. In general, due to the potentially costly consequences of a product recall, a firm tends to be reluctant to innovate when the post-innovation product failure probability is predicted to be high. However, an increase in failure probability may actually motivate more firms to invest in R&D. This is because a higher recall probability, combined with how testing decisions are made, can increase the likelihood that the two products will be differentiated on the vertical dimension; or that a firm will become a dominant player in the market if only its rival incurs a recall and goes bankrupt. The prospects of the resulting higher expected profits, exactly because of a greater recall likelihood, is what drives both firms to innovate.

Lastly, from a regulatory perspective, imposing a stronger penalty in the event of a product recall or enforcing stricter standards for issuing a recall in an attempt to protect consumers can paradoxically increase the incidence of recalls, thereby jeopardizing consumer safety and well-being. This is because such higher costs may inadvertently prompt firms to rush to market with their untested and potentially hazardous innovations, as doing so increases the prospects of rivals’ bankruptcy. Hence, regulators should be cautious about such firm behaviors when setting their policies.[18]

[18] We thank an anonymous reviewer for suggesting this public policy implication.

Although we believe our model captures many of the underlying factors influencing firms' behavior in deciding whether to conduct quality assurance testing of their innovations, and we have checked their robustness in a number of alternative settings, we acknowledge several limitations of our study. First, to focus on aspects directly associated with a product recall, we assumed no differences across the firms in terms of the degree of innovation. In reality, asymmetries in the extent of product improvement often exist, which could be linked to differences in subsequent failure probabilities (e.g., greater improvements may increase the chances of malfunctions). These issues could affect the results by creating additional considerations for quality assurance testing, early launch, or even the ex-ante decision to innovate. Second, for simplicity, we assumed that latent product defects are readily discovered and addressed through quality assurance testing in a single time period. However, in practice, the duration of testing might depend on the complexity of potential flaws or testing could discover defects that cannot be rectified at all; negating the value of introducing the innovation.[19] To formally model these types of circumstances, the product testing structure would have to account for the duration of testing and the ability to fix uncovered defects. How these issues would affect firm behavior is not immediately obvious and would require examination that is beyond the scope of this study. Third, our study examines how a recall can affect the perceived value of a single innovation across two periods. However, in a multi-innovation model, the implications of a recall (or lack thereof) could extend to affect consumers' perceptions of the firm's future-generation product reliability and thus recall likelihood. This carry-over effect would obviously impact firms' incentives to conduct testing, and introduce considerations such as building up on or milking past reputation for delivering "problem-free" innovations. It would be intriguing for future research to explore the implications that a multi-innovation reputation scenario may entail. Lastly, we assumed that a product failure automatically triggers a recall and that the firm must bear the associated costs. In practice, product recalls are categorized as voluntary (issued by the firm) or involuntary (mandated by regulators, e.g., the CPSC). Hence, one can envision situations in which a firm discovers a problem and must decide whether to voluntarily issue a product recall. Such a decision would be based on the trade-off between incurring the pecuniary cost of a recall with certainty vs. risking a potentially greater cost and extensive reputation damage if an involuntary recall is imposed. Though these topics are not addressed in this study given our focus, they present exciting avenues for future research.

[19] For example, Apple showcased a working version of AirPower, a wireless charging mat, in September 2017. However, after a prolonged 1.5 years of testing, it suspended the product's development in March 2019, noting that "After much effort, we've concluded AirPower will not achieve our high standards and we have cancelled the project."

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