Product Liability, Multidimensional RD and Innovation

Lin, Ping and Zhang, Tianle

Lingnan University, Lingnan University

November 2019

Product Liability, Multidimensional R&D and Innovation

Ping Lin* Tianle Zhang†

November 14, 2019

Abstract: We study the effect of product liability on the incentives of product and safety innovation. We first develop a monopoly model in which a firm chooses both product novelty and safety in an innovation stage followed by a production stage. A greater product liability directly increases the marginal benefit of producing a safer product and thus increases product safety. However, as product liability increases, product novelty may increase or decrease, depending on the relative strengths of demand-shifting and cross-R&D effects identified in the model. Consequently, a greater product liability may decrease consumer welfare and thus total welfare. We extend the results to an oligopoly model with differentiated products and study the effects of competition measured by the number of firms and the degree of product substitutability. We find that equilibrium product novelty and safety decrease with the number of firms but exhibit non-monotonic relationships with the degree of product substitutability.

Keywords: Product Liability, Safety, Novelty, Innovation Incentive
JEL Classifications: K13, L13, D43

*Lingnan University, Hong Kong; pinglin@ln.edu.hk
†Lingnan University , Hong Kong; tianlezhang@ln.edu.hk

We would like to thank participants at Asia-Pacific Industrial Organisation Conference at University of Melbourne and Hong Kong Economic Association Biennial Conference at Xiamen for their helpful comments.

I. INTRODUCTION

One central question in economics of innovation is how to provide the appropriate incentives for firms to conduct innovation. Product liability plays an important role in influencing firms' innovation decisions. For example, toy manufacturers may be concerned about whether their products with newly incorporated functions would cause harm to children, and pharmaceutical producers may be afraid of unknown side effects for recently developed drugs. As the harm done to consumers may result in court litigation, which could cost millions of dollars, producers may hesitate to launch innovative products if the product liability is high. In fact, in a survey conducted by Mcguire (1988), more than a third of surveyed CEOs reported that product liability had a major effect on their business, and a small share reported abandoning a new product because of liability fears. In addition to the concern of inventing unsafe products, firms may want to improve the safety of their existing products to avoid potential litigation in court. A case in point is the recent accident involving the explosion of a Samsung Note 7. The lawsuits it may cause highlight the potential monetary loss and reputation damage done to innovating firms under product liability. According to Polinsky and Shavell (2010), in the United States, tens of thousands of product liability cases are filed annually in court.

This paper aims to study the effect of product liability in economic environments where firms behave strategically when conducting product innovations. In particular, we first consider a monopoly model in which a firm chooses both product novelty and safety in an innovation stage followed by a production stage. Our framework captures the firm's interdependent choices of product novelty and safety which influence consumer demand and determine R&D costs. In the model, a greater product liability directly increases the marginal benefit of inventing a safer product and thus increases product safety. However, the effect on product novelty is more subtle. On the one hand, there is a *demand-shifting effect*: an increase in product safety induces a higher consumer demand, which provides incentives for the firm to increase product novelty. On the other hand, there is *a cross-R&D effect*: a higher product safety may increase or decrease the marginal R&D cost of product novelty. The overall effect of product liability on product novelty depends on the relative strengths of these two effects. One finding from the model is that both product novelty and safety increase with product liability when their R&D costs are independent. This result contrasts with those of Viscusi and Moore (1993), who find that product liability has no effect on product and safety innovation if the R&D costs are independent.

Interestingly, we show that an increase in product liability that seems to protect consumers may actually lead to lower consumer welfare. This arises when the negative cross-R&D effect is relatively large, in which case the firm optimally raises the product safety but lowers the product novelty. The reduced product novelty negatively affects consumer welfare to the extent that it dominates the consumer benefit of increased product safety. Consequently, a higher product liability may result in lower consumer welfare and thus lower total welfare.

We extend the model to an oligopoly case where n symmetric firms first simultaneously choose product novelty and safety, and then compete in a product market. We show that the results in the monopoly model can be readily extended to the competitive setting. We also study the effect of competition, which is measured, respectively, by the number of firms and degree of product substitutability. We show that equilibrium product novelty and safety decrease as the number of firms increases. This is because an increase in the number of firms reduces the equilibrium output for each firm and thus leads to a lower equilibrium product novelty and safety. However, as the degree of product substitutability increases, equilibrium product novelty and safety decrease initially and then increase. Two forces are behind this non-monotonic pattern. First, closer substitutes lead to a lower equilibrium output, resulting in a lower product novelty and safety due to a weakened demand-shifting effect. Second, the reduced product differentiation provides a higher incentive for firms to invest in product novelty. Furthermore, we show that product liability and competition measured by the number of firms are substitutes in the promotion of product and safety innovation, while an increase in product substitutability may strengthen or weaken the effects of product liability on product novelty and safety innovation.

The existing literature of product liability and innovation incentive has focused on the pure incentive of product innovation.[1] A dominant view is that greater product liability deters product innovation because it reduces profits from innovation and thus the likelihood of introducing new products (Porter 1980). Several recent papers have studied issues related to product safety. Daughety and Reinganum (1995) study the choice of R&D investment safety under various liability systems. Chen and Hua (2012) examine the effects of product liability on ex ante safety investment and possible ex post remedy. Daughety and Reinganum (2006) compare the market equilibrium safety effort and output levels to what a planner would choose. Baumann and Heine (2013) consider the role of product liability in innovation when firms face competitive pressure and find that compared with social optimum, competition forces innovating firms to introduce new products too early. Chen and Hua (2017) investigate whether competition can substitute for product liability in motivating firms to improve product safety. However, none of these studies considers the effect of product liability on firms' joint decision on product novelty and safety as we do in this paper.[2]

Our paper closely relates to Viscusi and Moore (1993) in which a reduced form model is developed to study the effect of product liability on both safety and product innovation. Differently, we develop a game theoretical model under monopoly and oligopoly situations in which firms make strategic decisions. Consequently, compared with Viscusi and Moore, we obtain different results (in the monopoly model) and new insights (in the competition setting). For example, we show that both product novelty and safety increase with product

[1] See Daughety and Reinganum (2013) for a survey on recent theoretical economic analysis of product liability. Studies have examined alternative protections for consumers under product failure (e.g., product warranties (Cooper and Ross, 1985) and product recall (Hua, 2011).)

[2] Chen (2001) develops a green product model in which the monopoly firm chooses both traditional and environmental attributes for its products to satisfy different segments of consumers.

liability, whereas Viscusi and Moore find that product liability has no effect on product and safety innovation if their R&D costs are independent. Moreover, we study the effect of competition, whereas Viscusi and Moore merely consider the case of a monopoly firm.

The rest of the paper proceeds as follows. We present a monopoly model and illustrate its economic forces in Section 2. We extend the model to an oligopoly setting and study the effect of competition in Section 3. Section 4 concludes the paper. All proofs are regulated in the Appendix A.

II. A MONOPOLY MODEL

In this section, we study a monopoly model to illustrate the economic forces in a transparent way. In the next section, we consider the case of competition.

The setup

Consider a case where a monopoly firm conducts product innovation and invents a new product that has two dimensions: a level of product novelty, $\gamma \geq 0$, and a degree of safety, $0 \leq s \leq 1$. A representative risk-neutral consumer derives utility from the new product,

$$U(q) = A(\gamma)\, q - \frac{1}{2} q^2,$$

where q is the consumed quantity. We assume that consumer utility increases at a decreasing rate as product novelty increases: $\partial A / \partial \gamma > 0$ and $\partial^2 A / \partial \gamma^2 \leq 0$.

The new product entails a safety risk that may cause harm to the consumer. In particular, with a probability s, the new product is dysfunctional and the consumer suffers a damage δ from product failure. In many cases, the firm bears only partial responsibility because it may be difficult to verify the cause of product failure. Even if the firm is fully responsible for the damage, the consumer may still incur an uncompensated loss (settlement bargaining, litigation cost, etc.), which is denoted as $\varphi(s, \delta)$ (Daughety and Reinganum, 2006). We assume that the uncompensated loss increases with δ, $\partial\varphi/\partial\delta > 0$, and is a decreasing, convex function of product safety, $\partial\varphi/\partial s < 0$ and $\partial^2\varphi/\partial s^2 \geq 0$. Hence, the consumer maximizes

$$A(\gamma)\, q - \frac{1}{2}q^2 + y - pq - \varphi(s, \delta)\, q, \tag{1}$$

where p is the price and y is the income. We can derive the inverse demand function as

$$p = A(\gamma) - q - \varphi(s, \delta)\,. \tag{2}$$

The product innovation is costly. Specifically, the cost of inventing the new product with a level of novelty γ and a degree of safety s is $x(\gamma, s)$ with $\partial x/\partial\gamma > 0$, $\partial x/\partial s > 0$, $\partial^2 x/\partial\gamma^2 > 0$ and $\partial^2 x/\partial s^2 > 0$.[3] With a probability $1 - s$, the product is not safe and may cause damage to the consumer. In this case, the firm is demanded to pay a fine L. In our paper, a higher L means a higher product liability.[4] We assume that once the product is invented, it can be produced at a constant marginal cost c.

The timing is as follows. First, the degree of product liability, L, is determined. Second, the firm chooses a product novelty, γ, and a degree of safety, s. Third, the firm decides the quantity of output, q. Fourth, with a probability $1 - s$, the product is not safe, the firm pays L.

The analysis

We solve the model by backward induction. Consider the choice of output quantity, q, given product novelty, γ, and safety, s. The firm chooses q to maximize profit,

$$\pi = (p - c)\, q - (1 - s)\, L - x(\gamma, s)\,.$$

[3] Note that $\partial^2 x/\partial\gamma\partial s$ can be positive, negative or zero.

[4] In Appendix B, we consider the case in which product liability depends on quantity sold and show that main insights continue to hold.

From (2), the profit-maximizing quantity satisfies

$$q = \frac{A(\gamma) - \varphi(s, \delta) - c}{2}. \tag{3}$$

Next, we consider the choices of product novelty and safety. From (3), we can rewrite the profit function as

$$\pi = \left[\frac{A(\gamma) - \varphi(s, \delta) - c}{2}\right]^2 - (1 - s) L - x(\gamma, s). \tag{4}$$

The first-order conditions of (4) with respect to γ and s, respectively, yield

$$[A(\gamma) - \varphi(s, \delta) - c] \frac{\partial A}{\partial \gamma} - 2\frac{\partial x}{\partial \gamma} = 0 \tag{5}$$

and

$$-[A(\gamma) - \varphi(s, \delta) - c] \frac{\partial \varphi}{\partial s} + 2L - 2\frac{\partial x}{\partial s} = 0. \tag{6}$$

The second-order conditions, which we assume to hold, are

$$\left(\frac{\partial A}{\partial \gamma}\right)^2 + [A(\gamma) - \varphi(s, \delta) - c] \frac{\partial^2 A}{\partial \gamma^2} - 2\frac{\partial^2 x}{\partial \gamma^2} < 0\,, \left(\frac{\partial \varphi}{\partial s}\right)^2 - [A(\gamma) - \varphi(s, \delta) - c] \frac{\partial^2 \varphi}{\partial s^2} - 2\frac{\partial^2 x}{\partial s^2} < 0 \tag{7}$$

and

$$\begin{aligned} \Phi \;=\; & \left\{\left(\frac{\partial A}{\partial \gamma}\right)^2 + [A(\gamma) - \varphi(s, \delta) - c] \frac{\partial^2 A}{\partial \gamma^2} - 2\frac{\partial^2 x}{\partial \gamma^2}\right\} \left\{\left(\frac{\partial \varphi}{\partial s}\right)^2 - [A(\gamma) - \varphi(s, \delta) - c] \frac{\partial^2 \mu}{\partial s^2} - 2\frac{\partial^2 x}{\partial s^2}\right\} \\ & - \left(\frac{\partial A}{\partial \gamma}\frac{\partial \varphi}{\partial s} + 2\frac{\partial^2 x}{\partial \gamma \partial s}\right)^2 > 0. \end{aligned} \tag{8}$$

We are now in a position to examine the effect of higher liability on product and safety innovations. Considering the total differentiations of (5) and (6) with respect to L, with rearrangements and by Cramer's rule, we have[5]

$$\frac{\partial s}{\partial L} = -\frac{2}{\Phi}\left\{\left(\frac{\partial A}{\partial \gamma}\right)^2 + \left[A(\gamma) - \varphi(s,\delta) - c\right]\frac{\partial^2 A}{\partial \gamma^2} - 2\frac{\partial^2 x}{\partial \gamma^2}\right\} \tag{9}$$

and

$$\frac{\partial \gamma}{\partial L} = -\frac{2}{\Phi}\left(\frac{\partial A}{\partial \gamma}\frac{\partial \varphi}{\partial s} + 2\frac{\partial^2 x}{\partial \gamma \partial s}\right). \tag{10}$$

From (7) and (8), we have $\frac{\partial s}{\partial L} > 0$. Moreover, $\frac{\partial \gamma}{\partial L} \gtreqless 0$ if $\Delta \gtreqless 0$, where

$$\Delta = -\frac{1}{2}\frac{\partial A}{\partial \gamma}\frac{\partial \varphi}{\partial s} - \frac{\partial^2 x}{\partial \gamma \partial s}. \tag{11}$$

We have the following proposition.

Proposition 1 *Suppose that* (γ^*, s^*), *which are interior solutions to (5) and (6), exist. (i)* s^* *increases in* L; *and (ii)* γ^* *increases (decreases) in* L *if* $\Delta > (<)0$. *Moreover, if* $\partial^2 x/\partial\gamma\partial s = 0$, *then both* s^* *and* γ^* *increase in* L.

A higher L directly increases the marginal benefit of improving product safety, as a safer product reduces the probability for the firm to pay L. Moreover, a higher product safety increases consumers' willingness to pay. The increased willingness to pay affects the firm's price and quantity and thus provides further incentive to increase product safety. We term this the *demand-shifting effect*. The effect of L on product novelty is more subtle. Although an increase in L does not directly affect the choice of product novelty, it has two indirect effects. First, there is the *cross-R&D effect* on the R&D production side in the sense that a higher product safety may increase or decrease the marginal R&D cost of product novelty, which is represented by the last term in (11). In particular, if this cross-R&D effect is positive and significant, the firm has a strong incentive to lower the product novelty when the product safety increases. Second, as in product safety, there is the *demand-shifting*

[5] Derivations are shown in the proof of Proposition 1 in Appendix A.

effect. In particular, an increase in s leads to a higher willingness to pay, which influences the firm's price and quantity strategies and thus the marginal profit of increasing product novelty.[6] The demand-shifting and cross-R&D effects jointly determine the overall impact of L on equilibrium product novelty.

It is also worthy of pointing out that in our model, both equilibrium product novelty and safety increase in product liability if the cross-R&D cost effect is neutral. This result contrasts with those of Viscusi and Moore (1993), who conclude, "If there is no interaction between safety and novelty in the input requirement function $\cdots$ higher liability costs will affect safety investments but not product novelty." (page 167). Here, we go beyond Viscusi and Moore (1993) to consider a game-theorectical framework where consumers' demands on product novelty and safety are interdependent and thus a change in product liability affects both equilibrium product safety and novelty. With the absence of a cross-R&D effect, a higher L increases product novelty through the positive demand-shifting effect in our model.

To obtain further results, we consider the following linear demand and quadratic R&D cost specifications: (i) the product value consists of an (exogenous) essential value and a variable value that can be improved by the firm at a cost; (ii) the expected uncompensated damage is linear in product safety s; and (iii) the R&D cost is quadratic. In particular, we assume that

$$A(\gamma) = \gamma_0 + \gamma, \qquad \varphi(s, \delta) = (1 - s)\,\delta, \tag{12}$$

where γ_0 is the (exogenous) essential value of the product and

$$x(\gamma, s) = \frac{1}{2}\alpha\gamma^2 + \frac{1}{2}\beta s^2 + \sigma\gamma s, \qquad \alpha > 0, \beta > 0, \tag{13}$$

where α and β are the cost coefficients of product novelty and safety, respectively, and $\partial^2 x/\partial\gamma\partial s = \sigma$ captures the cross-R&D cost effect. Note that under (12) and (13), (8) is

[6] To see this, note that from (2) and (3), $\frac{1}{2}\frac{\partial A}{\partial \gamma} = -\frac{\partial p}{\partial \gamma}$. Thus, the first term in (11) can be rewritten as $\frac{\partial p}{\partial \gamma}\frac{\partial \varphi}{\partial s}$, which represents the effect of s on the marginal effect of γ on monopoly price.

equivalent to

$$\frac{\delta}{2}-\sqrt{\left(\frac{\delta^2}{2}-\beta\right)\left(\frac{1}{2}-\alpha\right)}<\sigma<\frac{\delta}{2}+\sqrt{\left(\frac{\delta^2}{2}-\beta\right)\left(\frac{1}{2}-\alpha\right)}. \tag{14}$$

Moreover, from (11), we can calculate $\Delta = \frac{\delta}{2} - \sigma$. From Proposition 1, we immediately have the following result.

Corollary 1 *Under (12) and (13), (i) if* $\frac{\delta}{2}-\sqrt{\left(\frac{\delta^2}{2}-\beta\right)\left(\frac{1}{2}-\alpha\right)}<\sigma\leq\frac{\delta}{2}$, *then* $\frac{\partial s}{\partial L}\geq 0$ *and* $\frac{\partial \gamma}{\partial L}\geq 0$; *and (ii) if* $\frac{\delta}{2}<\sigma<\frac{\delta}{2}+\sqrt{\left(\frac{\delta^2}{2}-\beta\right)\left(\frac{1}{2}-\alpha\right)}$, *then* $\frac{\partial s}{\partial L}>0$ *and* $\frac{\partial \gamma}{\partial L}<0$.

The overall effect of product liability on product novelty depends on the relative strengths of the demand-shifting and cross-R&D cost effects. When σ is small, the cross-R&D cost effect is relatively less significant. Thus, the positive demand-shifting effect dominates, and consequently a higher L increases both s and γ. When σ is large, the negative cross-R&D cost effect outweights the demand-shifting effect. As a result, an increase in L causes γ to decline.

How does consumer welfare change with product liability? In Proposition 1, we show that as product liability increases, product safety increases. However, the firm may choose a higher or a lower product novelty. Hence, consumers can be worse off because of a possibly lower product novelty even if they benefit from a safer product. Thus, it is not clear ex-ante whether a higher product liability always benefits consumers or not. Next, we address this question.

Under quansi-linear consumer utility, the consumer welfare can be calculated from (1), where q takes the value of equilibrium output quantity. Using (2), we can show that consumer welfare is

$$CS=\frac{1}{2}\left[\frac{A(\gamma)-\varphi(s,\delta)-c}{2}\right]^2+y.$$

Thus,

$$\frac{dCS}{dL} = \frac{1}{2}q\left(\frac{\partial A}{\partial \gamma}\frac{\partial \gamma}{\partial L} - \frac{\partial \varphi}{\partial s}\frac{\partial s}{\partial L}\right). \tag{15}$$

In general, the effect of product liability on consumer welfare depends on the sign of $\frac{\partial \gamma}{\partial L}$, noting that $\frac{\partial \varphi}{\partial s}$ is negative and $\frac{\partial s}{\partial L}$ is positive. However, when there is no cross-R&D effect between product novelty and safety, from Proposition 1, an increase in product liability always leads to a higher product novelty and thus a higher consumer welfare. Under the linear consumer demand and quadratic R&D cost, we have the following result.

Proposition 2 *Under (12) and (13), consumer and total welfare increase (decrease) with product liability if* $\sigma < (>) \alpha\delta$.

Interestingly, a higher product liability may actually harm consumers. The intuition is as follows. If the cross-R&D effect captured by σ is large, the firm optimally raises the product safety but lowers the product novelty. The reduced product novelty negatively affects consumers to the extent that it dominates the consumer benefit of increased product safety. Consequently, the higher liability for the firm that seems to protect consumers may actually harm them. Moreover, by envelop theorem, we have $\frac{\partial \pi}{\partial L} = -(1-s)$. Thus, the sum of the firm's profit and its expected forfeited fine $(1-s)L$ is unchanged with L. Therefore, total welfare increases (decreases) with σ if $\sigma < (>) \alpha\delta$.

III. AN OLIGOPOLY MODEL AND COMPETITION

In this section, we develop an oligopoly model with product differentiation and extend the results in the previous section to the oligopoly model. We also study how competition, measured by the number of firms and product substitutability, respectively, affects the market equilibrium.

The setup and its equilibrium

There are n symmetric firms in the market, where firm i, $i = 1, ..., n$, can choose two dimensions for its product, a level of product novelty, $\gamma_i \geq 0$, and a degree of safety, $0 \leq s_i \leq 1$. We assume that the inverse demand function is

$$p_i = A(\gamma_i) - q_i - \varphi(s_i, \delta) - \theta \Sigma q_{-i},$$

where Σq_{-i} is the total output excluding q_i and $\theta \in (0, 1)$ captures the degree of substitutability among products.[7] Note that in a symmetric case where $\gamma_i = \gamma$ and $s_i = s$, for all i, the preceding demand functions reduce to those that are commonly used in the literature (Dixit, 1979). The cost of inventing a product with (γ_i, s_i) for firm i is denoted as $x(\gamma_i, s_i)$. Moreover, these costs are assumed i.i.d. among firms. The marginal cost of production is c once a product is invented.

The timing is stated as follows. First, the degree of product liability, L, is announced. Second, each firm decides product novelty and degree of safety. Third, after observing other firms' choices of product novelty and safety, each firm chooses its product quantity. Firms compete with each other in the output market. Fourth, in the case of product failure, the producer pays L.

Again, we solve the oligopoly model by backward induction. In particular, we first derive the optimal choice of output quantity given product novelty and safety and then characterize the optimal product novelty and safety in the symmetric equilibrium, where each firm chooses the same γ and s. In Appendix A, we show the following result.

Proposition 3 *In the oligopoly model, suppose a symmetric equilibrium exists such that*

[7] One can also derive this inverse demand function from a micro-foundation similar to that in the monopoly model in Section II.

each firm chooses (γ^{**}, s^{**}). *(i)* s^{**} *increases in* L *and (ii)* γ^{**} *increases (decreases) in* L *if*

$$\Sigma = \xi(n,\theta)\left(-\frac{\partial\varphi}{\partial s}\frac{\partial A}{\partial\gamma}\right) - \frac{\partial^2 x}{\partial\gamma\partial s} > (<) 0, \tag{16}$$

where

$$\xi(n,\theta) = \frac{2\left[2+(n-2)\theta\right]}{(2-\theta)\left[2+(n-1)\theta\right]^2}. \tag{17}$$

As in the monopoly case, a higher L induces a higher equilibrium product safety by increasing its marginal benefit. The effect of L on product novelty is subject to demand-shifting and cross-R&D cost effects. The overall effect of L on product novelty depends on specific forms of utility and cost functions. It is worthy of noticing that the introduction of an oligopoly model with product differentiation alters the magnitude of the two effects and thus the total effect on product novelty and safety. We address this issue in detail in the next subsection.

Suppose further that

$$A(\gamma_i) = \gamma_0 + \gamma_i, \qquad \varphi(s,\delta) = (1-s_i)\,\delta \tag{18}$$

and

$$x(\gamma_i, s_i) = \frac{1}{2}\alpha\gamma_i^2 + \frac{1}{2}\beta s_i^2 + \sigma\gamma_i s_i. \tag{19}$$

Under (18) and (19), the effects of product liability are

$$\frac{\partial s}{\partial L} = -\frac{\xi(n,\theta)-\alpha}{\left[\xi(n,\theta)\,\delta^2-\beta\right]\left[\xi(n,\theta)-\alpha\right]-\left[\xi(n,\theta)\,\delta-\sigma\right]^2} \tag{20}$$

and

$$\frac{\partial \gamma}{\partial L} = \frac{\xi(n,\theta)\,\delta-\sigma}{\left[\xi(n,\theta)\,\delta^2-\beta\right]\left[\xi(n,\theta)-\alpha\right]-\left[\xi(n,\theta)\,\delta-\sigma\right]^2}. \tag{21}$$

The next corollary immediately follows from Proposition 2.

Corollary 2 *In a symmetric equilibrium under specifications (18) and (19), (i) if* $\sigma \leq \xi\delta$, *then* $\frac{\partial s}{\partial L} \geq 0$ *and* $\frac{\partial \gamma}{\partial L} \geq 0$; *and (ii) if* $\sigma > \xi\delta$, *then* $\frac{\partial s}{\partial L} > 0$ *and* $\frac{\partial \gamma}{\partial L} < 0$.

Corollary 2 is a parallel result of Corollary 1. In the oligopoly model, when σ is relatively small ($\sigma \leq \xi\delta$), the positive demand-shifting effect is more prominent, and thus a higher L increases γ. However, when σ is relatively large ($\sigma > \xi\delta$), the negative cross-R&D cost effect dominates, and as a result, γ decreases as L increases.

The effect of competition

We next consider the effect of competition. In particular, we measure an increase in competition by (a) an increase in the number of firms, n, and (b) an increase in product substitutability, θ. To better illustrate the effect of competition, we focus on the case where both product novelty and safety increase with product liability. In particular, we assume $\sigma \leq \xi\delta$ such that, from Corollary 2, $\frac{\partial s}{\partial L} \geq 0$ and $\frac{\partial \gamma}{\partial L} \geq 0$.

We establish some useful results in the following lemma.

Lemma 1 *(i) As* n *increases,* ξ *decreases; and (ii) as* θ *increases,* ξ *first decreases and then increases.*

We are now in a position to study the effect of competition. We show in Appendix A, that

$$\frac{\partial \gamma}{\partial \xi} = \frac{[\gamma_0 + \gamma - (1-s)\,\delta - c]\,(\beta - \delta\sigma)}{(\xi - \alpha)\left(\xi\delta^2 - \beta\right) - (\xi\delta - \sigma)^2} \tag{22}$$

and

$$\frac{\partial s}{\partial \xi} = \frac{[\gamma_0 + \gamma - (1-s)\,\delta - c]\,(\alpha\delta - \sigma)}{(\xi - \alpha)\left(\xi\delta^2 - \beta\right) - (\xi\delta - \sigma)^2}. \tag{23}$$

Utilizing Lemma 1, we have the following results.

Proposition 4 *(i) As* n *increases,* γ *and* s *decrease; and (ii) as* θ *increases,* γ *and* s *decrease initially and then increase.*

An increase in the number of firms reduces the equilibrium output for each firm. This in turn weakens the demand-shifting effect and thus leads to a lower equilibrium product novelty and safety. As products become more substitutable, equilibrium product novelty and safety are subjected to two opposing effects. On the one hand, the equilibrium output is lower for a smaller θ. This results in a lower product novelty and safety due to a weaker demand-shifting effect. On the other hand, the reduced (horizontal) product differentiation provides a higher incentive for firms to invest in the vertical aspects of a product. Consequently, an decrease in θ may increase product novelty and safety. In our model, if θ is relatively small, the first force dominates, and thus the equilibrium product novelty and safety increases with θ. If θ is relatively large, the second force is more prominent, and thus the equilibrium product novelty and safety decreases with θ.

We next consider how a change in competition influences the effects of product liability on product novelty and safety. From (20) and (21), we can show that

$$\frac{\partial\left(\frac{\partial s}{\partial L}\right)}{\partial \xi} = \frac{(\sigma - \alpha\delta)^2}{\left(\sigma^2 - 2\xi\sigma\delta + \alpha\xi\delta^2 - \alpha\beta + \beta\xi\right)^2} > 0 \tag{24}$$

and

$$\frac{\partial\left(\frac{\partial \gamma}{\partial L}\right)}{\partial \xi} = \frac{(\alpha\delta - \sigma)(\beta - \sigma\delta)}{\left(\sigma^2 - 2\xi\sigma\delta + \alpha\xi\delta^2 - \alpha\beta + \beta\xi\right)^2} > 0 \tag{25}$$

noticing that $\sigma < \min\{\beta/\delta, \alpha\delta\}$, which is implied by the second-order conditions to guarantee the interior solutions. From Lemma 1, we have the following proposition.

Proposition 5 *(i) As n increases, the marginal effects of product liability on product novelty and safety decrease; and (ii) as θ increases, the marginal effect of product liability on product novelty and safety decrease initially and then increase.*

Proposition 5 indicates that product liability and competition measured by the number of firms are substitutes in the promotion of product and safety innovation. This is because an increase in the number of firms weakens the demand-shifting effect and thus reduces the effect of product liability on product and safety innovations. Proposition 5 also suggests that an increase in product substitutability may strengthen or weaken the effect of product liability on product and safety innovations. In particular, when products are relatively more independent, an increase in product substitutability lowers the effectiveness of product liability on innovations. In contrast, when products are close substitutes, an increase in product substitutability raises the effectiveness of product liability on innovations.

CONCLUSION

We have developed theoretical models to study the effects of product liability on the incentive of product innovation. In our models, firms optimally choose product novelty and safety while considering the effects on both consumer demand and joint R&D costs. A greater product liability directly increases the marginal benefit of producing a safer product and thus increases product safety. However, a greater product liability may increase or decrease product novelty, depending on the relative strengths of the demand-shifting and cross-R&D effects.

Our paper offers new insights into the literature, provides empirically testable results and draws important policy implications. First, in a well-cited paper, Viscusi and Moore (1993) conclude that product liability has no effect on product and safety innovation if the R&D costs are independent. In contrast, by explicitly modeling the strategic effect on consumer demand, which is absent in the reduced form model of Viscusi and Moore, we show that under independent R&D costs, both product novelty and safety increase with product liability. Second, we find that if the cross-R&D effect is relatively large, a greater product liability may lead to lower consumer and total welfare. Thus, policy-makers should be cautious in reforming product liability law by lifting up product liability. Finally, we show that an increase in competition among firms can have complex effects on the incentives of product innovation. In particular, product liability and competition measured by the number of firms are substitutes in the promotion of product and safety innovation, while an increase in product substitutability may strengthen or weaken the effect of product liability on product and safety innovation. Future research that empirically tests the relationship between product liability and competition in the promotion of innovations is desirable.

APPENDIX A

Proof of Proposition 1.

Total differentiations of (5) and (6) with respect to L give

$$\left(\frac{\partial A}{\partial \gamma}\frac{\partial \gamma}{\partial L} - \frac{\partial \varphi}{\partial s}\frac{\partial s}{\partial L}\right)\frac{\partial A}{\partial \gamma} + \left[A\left(\gamma\right) - \varphi\left(s,\delta\right) - c\right]\frac{\partial^2 A}{\partial \gamma^2}\frac{\partial \gamma}{\partial L} - 2\left(\frac{\partial^2 x}{\partial \gamma^2}\frac{\partial \gamma}{\partial L} + \frac{\partial^2 x}{\partial \gamma \partial s}\frac{\partial s}{\partial L}\right) = 0$$

and

$$-\left(\frac{\partial A}{\partial \gamma}\frac{\partial \gamma}{\partial L} - \frac{\partial \varphi}{\partial s}\frac{\partial s}{\partial L}\right)\frac{\partial \varphi}{\partial s} + \left[A\left(\gamma\right) - \varphi\left(s,\delta\right) - c\right]\frac{\partial^2 \varphi}{\partial s^2}\frac{\partial s}{\partial L} + 2 - 2\left(\frac{\partial^2 x}{\partial s \partial \gamma}\frac{\partial \gamma}{\partial L} + \frac{\partial^2 x}{\partial s^2}\frac{\partial s}{\partial L}\right) = 0.$$

With rearrangement, we can further show that

$$\left\{\left(\frac{\partial A}{\partial \gamma}\right)^2 + \left[A\left(\gamma\right) - \varphi\left(s,\delta\right) - c\right]\frac{\partial^2 A}{\partial \gamma^2} - 2\frac{\partial^2 x}{\partial \gamma^2}\right\}\frac{\partial \gamma}{\partial L} + \left(-\frac{\partial \varphi}{\partial s}\frac{\partial A}{\partial \gamma} - 2\frac{\partial^2 x}{\partial \gamma \partial s}\right)\frac{\partial s}{\partial L} = 0$$

and

$$\left(-\frac{\partial A}{\partial \gamma}\frac{\partial \varphi}{\partial s} - 2\frac{\partial^2 x}{\partial s \partial \gamma}\right)\frac{\partial \gamma}{\partial L} + \left\{\left(\frac{\partial \varphi}{\partial s}\right)^2 + \left[A\left(\gamma\right) - \varphi\left(s,\delta\right) - c\right]\frac{\partial^2 \varphi}{\partial s^2} - 2\frac{\partial^2 x}{\partial s^2}\right\}\frac{\partial s}{\partial L} = -2.$$

Thus, applying Cramer's rule, we can solve $\frac{\partial \gamma}{\partial L}$ and $\frac{\partial s}{\partial L}$, and obtain expressions as in (9) and (10). From (7) and (8), we have $\frac{\partial s}{\partial L} > 0$. Moreover, $\frac{\partial \gamma}{\partial L} \gtreqless 0$ if $\Delta \gtreqless 0$. Finally, if $\frac{\partial^2 x}{\partial \gamma \partial s} = 0$, $\Delta > 0$ and thus $\frac{\partial \gamma}{\partial L} > 0$.

Proof of Proposition 2.

Note that

$$\frac{dCS}{dL} = \frac{1}{2}q\left(\frac{\partial A}{\partial \gamma}\frac{\partial \gamma}{\partial L} - \frac{\partial \varphi}{\partial s}\frac{\partial s}{\partial L}\right).$$

Under the linear consumer demand and quadratic R&D cost, we have

$$\begin{aligned}\frac{dCS}{dL} &= \left(\frac{1}{2}q\right)\left(-\frac{2}{\Phi}\right)[(-\delta + 2\sigma) - (-\delta)(1 - 2\alpha)] \\ &= \left(\frac{1}{2}q\right)\left(-\frac{2}{\Phi}\right)(2\sigma - 2\delta\alpha).\end{aligned}$$

Thus, $\frac{dCS}{dL} > (<) 0$ if $\sigma < (>) \alpha\delta$. Moreover, by envelop theorem, we have

$$\frac{\partial \pi}{\partial L} = -(1 - s).$$

Therefore, for $TS = CS + \pi + (1 - s)L$, it increases (decreases) with σ if $\sigma < (>) \alpha\delta$.

Proof of Proposition 3.

We first consider the choice of output quantity, q_i, given product novelty, γ_i and γ_j, and safety level, s_i and s_j. Firm i maximizes profit,

$$\pi_i = (p_i - c)\, q_i - (1 - s_i)\, L - x(\gamma_i, s_i).$$

First order condition, $\frac{\partial \pi_i}{\partial q_i} = 0$, implies

$$q_i = \frac{A(\gamma_i) - \varphi(s_i, \delta) - c - \frac{\theta}{2+\theta(n-1)}\Sigma_{j=1}^{n}\left[A(\gamma_j) - \varphi(s_j, \delta) - c\right]}{(2 - \theta)}.$$

Next, we consider the choice of product novelty and safety. Note that the profit can be written as

$$\pi_i = (q_i)^2 - (1 - s_i)\, L - x(\gamma_i, s_i).$$

First order conditions with respect to s_i and γ_i, respectively, yield

$$\frac{\partial \pi_i}{\partial s_i} = 2q_i \frac{\partial q_i}{\partial s_i} + L - \frac{\partial x}{\partial s_i} = 2q_i \frac{2+(n-2)\theta}{(2-\theta)[2+(n-1)\theta]}\left(-\frac{\partial \varphi}{\partial s_i}\right) + L - \frac{\partial x}{\partial s_i} = 0$$

and

$$\frac{\partial \pi_i}{\partial \gamma_i} = 2q_i \frac{\partial q_i}{\partial \gamma_i} - \frac{\partial x_i}{\partial \gamma_i} = 2q_i \frac{2+(n-2)\theta}{(2-\theta)[(2+(n-1)\theta)]}\frac{\partial A}{\partial \gamma_i} - \frac{\partial x}{\partial \gamma_i} = 0. \tag{26}$$

We focus on the symmetric equilibrium in which each firm chooses product novelty γ, safety s and output q. It follows that

$$q = \frac{A(\gamma) - \varphi(s,\delta) - c}{2+\theta(n-1)}. \tag{27}$$

Thus,

$$\frac{\partial \pi}{\partial \gamma} = \xi [A(\gamma) - \varphi(s,\delta) - c] \frac{\partial A}{\partial \gamma} - \frac{\partial x}{\partial \gamma} = 0 \tag{28}$$

and

$$\frac{\partial \pi}{\partial s} = \xi [A(\gamma) - \varphi(s,\delta) - c] \left(-\frac{\partial \varphi}{\partial s}\right) + L - \frac{\partial x}{\partial s} = 0 \tag{29}$$

where

$$\xi = \frac{2[2+(n-2)\theta]}{(2-\theta)[2+(n-1)\theta]^2}.$$

Note that second order conditions, which we assume to hold, are

$$\xi \left[\left(\frac{\partial \mu}{\partial \gamma}\right)^2 + (\mu(\gamma,s) - c)\frac{\partial^2 \mu}{\partial \gamma^2}\right] - \frac{\partial^2 x}{\partial \gamma^2} < 0, \qquad \xi \left[\left(\frac{\partial \mu}{\partial s}\right)^2 + [\mu(\gamma,s) - c]\frac{\partial^2 \mu}{\partial s^2}\right] - \frac{\partial^2 x}{\partial s^2} < 0 \tag{30}$$

and

$$\begin{aligned}\Omega \quad = \quad & \left[\xi\left(\left(\frac{\partial \mu}{\partial s}\right)^2 + (\mu(\gamma,s)-c)\frac{\partial^2 \mu}{\partial s^2}\right) - \frac{\partial^2 x}{\partial s^2}\right]\left[\xi\left(\left(\frac{\partial \mu}{\partial \gamma}\right)^2 + (\mu(\gamma,s)-c)\frac{\partial^2 \mu}{\partial \gamma^2}\right) - \frac{\partial^2 x}{\partial \gamma^2}\right] \\ & - \left[\xi\left(\frac{\partial \mu}{\partial \gamma}\frac{\partial \mu}{\partial s} + (\mu(\gamma,s)-c)\frac{\partial^2 \mu}{\partial s \partial \gamma}\right) - \frac{\partial^2 x}{\partial s \partial \gamma}\right]^2 > 0. \end{aligned} \tag{31}$$

Total differentiation of (28) and (29) with respect to L, with rearrangement, yield,

$$\left[\xi\left(\left(\frac{\partial A}{\partial\gamma}\right)^2+\left[A(\gamma)-\varphi(s,\delta)-c\right]\frac{\partial^2 A}{\partial\gamma^2}\right)-\frac{\partial^2 x}{\partial\gamma^2}\right]\frac{\partial\gamma}{\partial L}+\left[\xi\left(-\frac{\partial\varphi}{\partial s}\frac{\partial A}{\partial\gamma}\right)-\frac{\partial^2 x}{\partial\gamma\partial s}\right]\frac{\partial s}{\partial L}=0$$

and

$$\left[\xi\left(\frac{\partial A}{\partial\gamma}\frac{\partial\varphi}{\partial s}\right)-\frac{\partial^2 x}{\partial s\partial\gamma}\right]\frac{\partial\gamma}{\partial L}+\left[\xi\left(\left(\frac{\partial\varphi}{\partial s}\right)^2+\left[A(\gamma)-\varphi(s,\delta)-c\right]\left(-\frac{\partial^2\varphi}{\partial s^2}\right)\right)-\frac{\partial^2 x}{\partial s^2}\right]\frac{\partial s}{\partial L}=-1.$$

Therefore, we have

$$\frac{\partial s}{\partial L}=-\frac{1}{\Omega}\left[\xi\left(\left(\frac{\partial A}{\partial\gamma}\right)^2+\left[A(\gamma)-\varphi(s,\delta)-c\right]\frac{\partial^2 A}{\partial\gamma^2}\right)-\frac{\partial^2 x}{\partial\gamma^2}\right] \tag{32}$$

and

$$\frac{\partial\gamma}{\partial L}=\frac{1}{\Omega}\left[\xi\left(-\frac{\partial\varphi}{\partial s}\frac{\partial A}{\partial\gamma}\right)-\frac{\partial^2 x}{\partial\gamma\partial s}\right]. \tag{33}$$

From (30) and (31), we have $\frac{\partial s}{\partial L}>0$. Moreover, $\frac{\partial\gamma}{\partial L}\gtreqless 0$ if $\Sigma\gtreqless 0$ where

$$\Sigma=\xi\left(-\frac{\partial\varphi}{\partial s}\frac{\partial A}{\partial\gamma}\right)-\frac{\partial^2 x}{\partial\gamma\partial s}.$$

Proof of Lemma 1.

(i) From (17),

$$\frac{\partial\xi}{\partial n}=-\frac{2\theta\left[(n-3)\theta+2\right]}{(2-\theta)\left[(n-1)\theta+2\right]^3}<0 \tag{34}$$

for $\theta\in(0,1)$.

(ii) Note that

$$\frac{\partial\xi}{\partial\theta}=\frac{4(n-1)}{(\theta-2)^2\left[(n-1)\theta+2\right]^3}\lambda(\theta,n) \tag{35}$$

where $\lambda(\theta, n) = (n-2)\theta^2 + (5-n)\theta - 2$. Hence,

$$sign\left(\frac{\partial\xi}{\partial\theta}\right) = sign\left(\lambda(\theta, n)\right).$$

Moreover, $\lambda(\theta, n) < 0$ if $\theta = 0$ and $\lambda(\theta, n) > 0$ if $\theta = 1$. It follows that there exists a unique $\hat{\theta} > 0$ such that $\frac{\partial\xi}{\partial\theta} < 0$ for $\theta \in (0, \hat{\theta}]$ and $\frac{\partial\xi}{\partial\theta} > 0$ for $\theta \in (\hat{\theta}, 1)$.

Proof of Proposition 4.

In the symmetric equilibrium, product novelty and safety are given by (28) and (29). Total differentiations of (28) and (29) with respect to ξ, with rearrangement, give

$$\frac{\partial\gamma}{\partial\xi} = \frac{1}{Z}\left\{\begin{array}{c} \left[-\left[A(\gamma) - \varphi(s,\delta) - c\right]\frac{\partial A}{\partial\gamma}\right]\left[\xi\left(\frac{\partial\varphi}{\partial s}\right)^2 + \xi\left[A(\gamma) - \varphi(s,\delta) - c\right]\left(-\frac{\partial^2\varphi}{\partial s^2}\right) - \frac{\partial^2 x}{\partial s^2}\right] \\ -\left[\xi\left(-\frac{\partial\varphi}{\partial s}\right)\frac{\partial A}{\partial\gamma} - \frac{\partial^2 x}{\partial\gamma\partial s}\right]\left[-\left[A(\gamma) - \varphi(s,\delta) - c\right]\left(-\frac{\partial\varphi}{\partial s}\right)\right] \end{array}\right\} \tag{36}$$

and

$$\frac{\partial s}{\partial\xi} = \frac{1}{Z}\left\{\begin{array}{c} \left[\xi\left(\frac{\partial A}{\partial\gamma}\right)^2 + \xi\left[A(\gamma) - \varphi(s,\delta) - c\right]\frac{\partial^2 A}{\partial\gamma^2} - \frac{\partial^2 x}{\partial\gamma^2}\right]\left[-\left[A(\gamma) - \varphi(s,\delta) - c\right]\left(-\frac{\partial\varphi}{\partial s}\right)\right] \\ -\left[-\left[A(\gamma) - \varphi(s,\delta) - c\right]\frac{\partial A}{\partial\gamma}\right]\left[\xi\frac{\partial A}{\partial\gamma}\left(-\frac{\partial\varphi}{\partial s}\right) - \frac{\partial^2 x}{\partial s\partial\gamma}\right] \end{array}\right\} \tag{37}$$

where

$$\begin{aligned} Z \;=\; & \left[\xi\left(\frac{\partial A}{\partial\gamma}\right)^2 + \xi\left[A(\gamma) - \varphi(s,\delta) - c\right]\frac{\partial^2 A}{\partial\gamma^2} - \frac{\partial^2 x}{\partial\gamma^2}\right]\left[\xi\left(\frac{\partial\varphi}{\partial s}\right)^2 + \xi\left[A(\gamma) - \varphi(s,\delta) - c\right]\left(-\frac{\partial^2\varphi}{\partial s^2}\right) - \frac{\partial^2 x}{\partial s^2}\right] \\ & -\left[\xi\frac{\partial A}{\partial\gamma}\left(-\frac{\partial\varphi}{\partial s}\right) - \frac{\partial^2 x}{\partial s\partial\gamma}\right]\left[\xi\left(-\frac{\partial\varphi}{\partial s}\right)\frac{\partial A}{\partial\gamma} - \frac{\partial^2 x}{\partial\gamma\partial s}\right]. \end{aligned}$$

Under the specifications, (36) and (37) become

$$\frac{\partial\gamma}{\partial\xi} = \frac{\left[A(\gamma) - \varphi(s,\delta) - c\right](\beta - \delta\sigma)}{(\xi - \alpha)\left(\xi\delta^2 - \beta\right) - (\xi\delta - \sigma)^2}$$

and

$$\frac{\partial s}{\partial \xi} = \frac{[A(\gamma) - \varphi(s,\delta) - c](\alpha\delta - \sigma)}{(\xi - \alpha)\left(\xi\delta^2 - \beta\right) - (\xi\delta - \sigma)^2}.$$

From (31), $(\xi - \alpha)\left(\xi\delta^2 - \beta\right) - (\xi\delta - \sigma)^2 > 0$. Moreover, from (30), $\xi < \min\left\{\beta/\delta^2, \alpha\right\}$. Thus, together with the assumption $\sigma \leq \xi\delta$, we have $\sigma < \min\{\beta/\delta, \alpha\delta\}$. Hence, by Lemma 1, results in Proposition 4 follow.

APPENDIX B

In this appendix, we consider a variant of our main model in which a monopoly firm's liability is linear in quantity sold. Compared to the main model, there will be an additional quantity effect in the variant considered here because product quantity will depend on liability. The analysis will become more complicated. Nevertheless, we will show that the main insight that a higher product liability may induce a lower product novelty and consequently, lead to a lower consumer welfare will continue to hold under some parameter regions.

The setup is the same as in the main model except that liability L is equal to lq where l measures the strength of liability.[8] The following analysis is similar to that in the main model. In particular, the firm chooses q to maximize profit,

$$\pi = (p - c)\,q - (1 - s)\,lq - x(\gamma, s).$$

The resulting profit-maximizing quantity is

$$q = \frac{A(\gamma) - \varphi(s,\delta) - c - (1 - s)\,l}{2}.$$

[8] Daughety and Reinganum (2006) adopt a similar setting to analyze the effect of market and legal incentives on the level of safety effort as well as the level of output.

and thus we can rewrite the profit function as

$$\pi = [q(\gamma, s, l)]^2 - x(\gamma, s). \tag{38}$$

The first-order conditions of (38) with respect to γ and s, respectively, yield

$$q\frac{\partial A}{\partial \gamma} - \frac{\partial x}{\partial \gamma} = 0 \tag{39}$$

and

$$q\left(-\frac{\partial \varphi}{\partial s} + l\right) - \frac{\partial x}{\partial s} = 0. \tag{40}$$

To conduct tractable analysis, we focus on the case with linear demand and quadratic cost function as considered in Corollary 1. In particular, from the total differentiations of (39) and (40) with respect to l, we can obtain that

$$\frac{\partial s}{\partial l} = \frac{1}{\Theta}\left\{\left(\alpha - \frac{1}{2}\right)\left[q - \frac{(1-s)}{2}(\delta + l)\right] + \frac{(1-s)}{2}\left[\sigma - \frac{1}{2}(\delta + l)\right]\right\} \tag{41}$$

and

$$\frac{\partial \gamma}{\partial l} = \frac{1}{\Theta}\left\{\frac{(1-s)}{2}\left[\frac{1}{2}(\delta + l)^2 - \beta\right] - \left[\frac{1}{2}(\delta + l) - \sigma\right]\left[\frac{(1-s)}{2}(\delta + l) - q\right]\right\} \tag{42}$$

with

$$\Theta = \left[\frac{1}{2} - \alpha\right]\left[\frac{1}{2}(\delta + l)^2 - \beta\right] - \left[\sigma - \frac{1}{2}(\delta + l)\right]^2.$$

Moreover, assuming γ and s are interior solution, we have, from the second-order condition, $\alpha > \frac{1}{2}$, $\beta > \frac{1}{2}(\delta + l)^2$ and $\Theta > 0$.

Next, we can show that consumer welfare is

$$CS = \frac{1}{2}\left[\frac{A(\gamma) - \varphi(s, \delta) - c - (1-s)l}{2}\right]^2 + y.$$

Hence,

$$\frac{dCS}{dl} = \frac{1}{2}q\left[\frac{\partial \gamma}{\partial l} + (\delta + l)\frac{\partial s}{\partial l} - (1-s)\right]. \tag{43}$$

We have the following result.

Proposition 6 *Suppose that (γ^*, s^*), which are interior solutions to (39) and (40), exist. (i) s^* increases in l and γ^* decreases in l if $\sigma > \alpha(\delta + l)$ and $\beta > \sigma(\delta + l)$. Moreover, if $\beta > 2\sigma(\delta + l)$, then consumer surplus decreases in l.*

Proof. From (41),

$$\frac{\partial s}{\partial l} = \frac{1}{\Theta}\left\{\frac{(1-s)}{2}\left[\sigma - \alpha(\delta + l)\right] + \left(\alpha - \frac{1}{2}\right)q\right\}.$$

Hence, if $\sigma > \alpha(\delta + l)$, then $\frac{\partial s}{\partial l} > 0$ because $\alpha > \frac{1}{2}$.

Moreover, from (42),

$$\frac{\partial \gamma}{\partial l} = \frac{1}{\Theta}\left\{\frac{(1-s)}{2}\left[\sigma(\delta + l) - \beta\right] + \left[\frac{1}{2}(\delta + l) - \sigma\right]q\right\}.$$

Thus, if $\sigma > \alpha(\delta + l)$ and $\beta > \sigma(\delta + l)$, then $\frac{\partial \gamma}{\partial l} < 0$.

Finally,

$$\frac{dCS}{dl} = .\frac{1}{2}q\left[\frac{1}{\Theta}\left\{\frac{(1-s)}{2}\left[2\sigma(\delta + l) - \beta - \alpha(\delta + l)^2\right] + \left[-\sigma + (\delta + l)\alpha\right]q\right\} - (1-s)\right]$$

If $\sigma > \alpha(\delta + l)$ and $\beta > 2\sigma(\delta + l)$, then we have $\frac{dCS}{dl} < 0$. ■

The intuition behind Proposition 6 is similar to that in the main model. Specifically, an increase in l directly increases the marginal benefit of improving product safety. However, when the cross-R&D effect is large (σ is relatively large), an increase product safety induces a decrease in product novelty. When the reduction in product novelty is large it will offset the benefit of an increase in product safety and consequently, consumer welfare will decrease.

REFERENCES

[1] Baumann, F. and Heine, K. (2013) "Innovation, Tort law, and competition", Journal of Institutional and Theoretical Economics, Vol. 169 (4), 703-719

[2] Chen, C. (2001), "Design for the Environment: A Quality-Based Model for Green Product Development", Management Science, Vol. 47, No. 2, pp. 250-263.

[3] Chen, Y. and Hua, X., (2012) “Ex ante Investment, Ex post Remedy, and Product Liability” International Economic Review, Vol. 53, 845-866

[4] Chen, Y. and Hua, X., (2017), "Competition, Product Safety, and Product Liability", Journal of Law, Economics, and Organization, Vol. 33, 237-267.

[5] Cooper, R. and Ross, T., (1985), “Product Warranties and Double Moral Hazard”, Rand Journal of Economics, Vol. 16, No. 1, pp. 103-113

[6] Daughety, A. and Reinganum, J., (1995). “Product Safety: Liability, R&D and Signaling,” American Economic Review 85(5), 1187-1206.

[7] Daughety, A. and Reinganum, J. (2006). “Market, Torts, and Social Inefficiency.” 37 Rand Journal of Economics 300-323

[8] Daughety, A. and Reinganum, J. (2013). “Economic Analysis of Products Liability: Theory”, Chapter 3 in the Research Handbook on the Economics of Torts, edited by Jennifer Arlen, Edward Elgar Publishing Co., Cheltenham, U.K., pp. 69-96.

[9] Dixit, A., (1979) "A Model of Duopoly Suggesting a Theory of Entry Barriers", Bell Journal of Economics, Vol. 10, No. 1. pp20-32

[10] Hua, X. (2011). “Product Recall and Liability.” The Journal of Law, Economics, and OrganizationVol. 27.

[11] Mcguire, E., (1988), "The Impact of Product Liability", The Conference Board Research Report, New York, NO. 908 6-20

[12] Polinsky, A., and Shavell, S., (2010), "The Uneasy Case for Product Liability", Harvard Law Review, Vol. 123, No. 6.

[13] Porter, M., (1990) "The Competitive Advantage of Nations". New York: Free Press.

[14] Viscusi, W. and Moore, M., (1993) "Product Liability, Research and Development, and Innovation" Journal of Political Economy, Vol. 101, No. 1, pp. 161-184