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Japan and the World Economy
17 (2005) 59–81

Japan and the WORLD ECONOMY

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The effects of product liability costs on R&D with asymmetric information

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Received 5 August 2002; received in revised form 16 September 2003; accepted 7 October 2003

Abstract

This paper examines the effects of product liability costs on R&D with asymmetric information. When the product is defective, both the consumer and producer share the resulting losses. This paper explores the impacts of liability costs on the firm's R&D decisions in three information structures: full information; hidden information; and hidden information and hidden action. It is found that the effects differ across information structures. This paper also compares the equilibrium amounts of R&D and social welfare levels across three cases. Equilibrium R&D is smaller than the socially optimal level for each information structure.

JEL classification: K13; L15; D42; D8

Keywords: Product liability; Monopoly; Quality; R&D; Signaling

1. Introduction

There are many product markets where the perfect information assumption, namely, both consumers and producers have complete knowledge of product quality, cannot be adopted. Often information is asymmetric so that the producer knows about the quality of his/her product, but prior to use the consumer does not. Examples of products with these characteristics include pharmaceuticals, electronic goods and automobiles. This paper develops a monopoly model of prices and R&D as signals of product quality based on Daughety and Reinganum (1995) in order to examine the effects of product liability costs on R&D, and to compare the non-co-operative and welfare-maximizing R&D investment

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0922-1425/$ – see front matter
doi:10.1016/j.japwor.2003.10.001

levels. Quality in this paper is represented by the probability that the product is defective. When the product is defective, not only the consumer, but also the producer share the losses caused by a manufacturing defect. Liability costs are incorporated into both the firm's profit function and the consumer's budget constraint.

This paper investigates how the consumer perceives product quality by observing the available information. Three different information structures are examined; (1) complete information where there is neither hidden information nor hidden action, that is the consumer has knowledge of both information and action; (2) hidden information only, where the consumer knows only the firm's action, but not the product quality; and (3) hidden information and hidden action, where the consumer has knowledge of neither the firm's investment nor the product's quality.

In contrast to papers like Cooper and Ross (1985a), Bagwell and Riordan (1991) and Judo and Riordan (1994) where higher prices signal higher quality, in this paper, it is found that the price-quality relationship is not so straightforward. If the firm's marginal cost of product risk per unit is positive (negative), a low (high) price and a large (small) amount of R&D signal high quality. Since the liability cost of defective goods is incorporated into the firm's profit function, and quality affects both production and liability costs, a marginal improvement in quality has two different effects; an increase in production costs and a decrease of liability costs.

This paper makes three important contributions. First, it is shown that the effects of product liability on R&D differ among information structures. That is, whether the consumer has knowledge of only product quality or both quality and R&D will affect the firm's equilibrium level of R&D. When the consumer does not have perfect information about product quality, product liability costs also have an impact on the firm's R&D decision. These results have important implications for empirical modeling of movements in R&D expenditure at the firm level. The paper's second contribution is that by setting out a model with three different information structures, it is possible to make explicit welfare comparisons among the information structures, whereas much of the signaling literature focuses solely on the firm's strategy. The third contribution is this paper considers not only price, but also the level of R&D, as a signal of product quality. Of course, the existing literature contains many papers on multiple signals, and other potential signals in addition to price. For example, Wilson (1985), Quinzii and Rochet (1985) and Engers (1987) consider problems with multi-dimensional signals. Papers discussing the use of advertising as a signal include Schmalensee (1978), Kihlstrom and Riordan (1984), Klein and Leffler (1981), Milgrom and Roberts (1986), Bagwell and Ramey (1994a,b), Caves and Greene (1996) and Lutz and Padmanabhan (1998). The relationship between warranty and product quality is examined by Spence (1977), Grossman (1981) and Cooper and Ross (1985b) [1]. R&D serves as a signal of product quality via the product price channel in this model. The firm's decisions on R&D are compared across three information structures.

The relationships between price, quality and product liability have already been the subject of extensive research. For example, Cooter (1991) and Kaplow and Shavell (1999) provide surveys of the economic analysis of liability. However, their analysis have completely overlooked the possibility that signaling of product quality through price

[1] The criterion for eliminating the out-of-equilibrium beliefs is presented in Cho and Kreps (1987).

and R&D can be used as an alternative to using changes in the liability as a means to reduce risk. The classic papers by Brown (1973), Hamada (1976, 1995) analyze liability rules and their effects on the price system. Stiglitz (1987) and Riley (2001) provide comprehensive surveys of the relationship between price and quality. The possibility that prices may serve as signals in markets where the firm has private information and the consumer has only imperfect information about quality has been demonstrated by a large literature (for example, Wolinsky, 1983). Although Wolinsky (1983) assumes that producers can choose quality endogenously and the price is the only signal, here price and the level of R&D investment are shown to be signals, and quality is assumed to be determined exogenously. Shieh (1993) examines the incentives for investment in a signaling model with both hidden information (about quality) and action (about investment), but unlike this paper product liability costs are not included in the model and R&D investment is not a signal of quality. Unlike Shieh (1993), who examines the relationship between product quality and investment, this paper focuses on the relationship between product liability costs and R&D investment. As shown in Proposition 5, I find that R&D investment may be enhanced or weakened by high product liability costs, while Shieh (1993) finds that asymmetric information about quality may strengthen or weaken a firm's incentive to engage in R&D investment.

Many papers discuss the relationship between price, R&D and quality in signaling models, however, few papers explicitly take into consideration the liability specification. An exception is Daughety and Reinganum (1995) who derive a price-safety relationship, and the firm's demand for safety regulation. The firm in this paper is a monopolist and engages in cost-reducing R&D which does not lead to any externality or spillover effect, and does not affect product quality. Daughety and Reinganum (1995) consider only the price-liability signaling. Incorporating R&D investment as a signal, unlike Daughety and Reinganum (1995), this paper finds that the increase of product liability costs may enhance or weaken R&D investment and compares the non-co-operative and welfare-maximizing levels of R&D investment. As Shy's (1995) survey indicates there are various dimensions and effects of R&D, but to highlight the role of R&D as a signal, this paper ignores many other crucial aspects of R&D activities including models of co-operation with spillover effects (see d'Aspremont and Jacquemin, 1988), the effects of R&D cartelization and joint research ventures (see Kamien et al., 1992), and R&D incentive instruments (de Laat, 1997).

This paper differs from the existing literature in the following three respects. First, two cases are considered: one case is where the amount of R&D is public information and a signal of product quality; and the other case is where the amount of R&D is the firm's private information and not a signal. Second, the effect of product liability costs on the level of R&D is clearly defined in each information structure. Third, explicit welfare comparisons and a characterization of the socially optimal levels of R&D are made. Although there are several signaling models including R&D stages, these models either assume that the consumer is not able to observe the level of R&D, or they do not treat R&D as a signal (for example, Shieh, 1993).

The effect of liability costs on R&D is estimated in Viscusi and Moore's (1993) empirical analysis. Their simple theoretical analysis does not consider either the information structure or the allocation of product liability costs between the firm and the consumer.

Here, it is demonstrated that both the information structure and the allocation of product liability costs will affect the firm's R&D decisions. While demand is treated as being *exogenously* determined in Viscusi and Moore (1993), here liability costs are explicitly incorporated into the consumer's budget constraint. Viscusi and Moore's (1993) theoretical model predicts that an increase in the firm's liability will cause R&D to *decrease*. In contrast, their empirical results suggest that at the sample mean, an increase in liability costs leads to a statistically significant *increase* in R&D intensity of 15 percent. This paper provides a theoretical justification for Viscusi and Moore's (1993) findings since that with hidden information an increase in the firm's liability is shown to always leads to an *increase* in R&D expenditure.

The paper is organized as follows. Section 2 sets out the basic model which builds on the work of Daughety and Reinganum (1995). A model where the consumer has knowledge of both product quality and firm's investment is presented in Section 3. Section 4 analyzes a model where both cost-reducing R&D and price serve as signals of quality. The R&D levels that arise with the three different information structures are compared in Section 5. The effects of product liability on R&D are shown in Section 6. Section 7 examines whether the firm has an incentive for information revelation. Section 8 characterizes the socially optimal level of R&D and makes explicit welfare comparisons between the three different information structures. Consumer beliefs in the model are explored in Appendix A, while Appendix B examines the price distortion between the information structures.

2. The model

This paper combines the price-safety model of Daughety and Reinganum (1995) with a model of cost-reducing R&D in order to examine the effects of product liability costs on R&D and to compare the non-co-operative and welfare-maximizing levels of R&D investment.

A market where there are two players, a representative consumer and a monopolist, is considered. The monopolist firm produces a product with quality, $\theta \in [0, 1]$, which represents the probability that a unit is defective, that is, the higher the value of θ, the lower the quality of the product. This quality is assumed to be determined exogenously. The firm also engages in cost-reducing R&D. At minimum, the consumer knows that the amount of R&D, x, affects the product price, p.

The model uses a two-stage approach and the properties of subgame-perfect equilibrium. In the first stage, the firm chooses its R&D level, and in the second stage, it then sets the price and sells the product.

This paper compares three different information structures that differ in how much the consumer knows about product quality ("information") and the firm's level of R&D expenditure ("action"). In the first case, there is neither hidden information nor a hidden action, that is, the consumer has knowledge of both product quality and the firm's investment in R&D. In the second case, there is hidden information only, so that the consumer knows about the firm's investment action. In the third case, there is hidden information and a hidden action where the consumer has knowledge of neither the firm's R&D investment nor the product's quality.

When the product is defective, the model assumes that the total loss caused to society by a defective product, L, is shared between the firm and the consumer. The total loss is assumed to be determined exogenously. This section presents a minimal explanation of a parametric liability specification (see Daughety and Reinganum, 1995 for a more detailed explanation). As Cooter (1991) argues, a reasonable liability system would require L_C, the uncompensated loss to the consumer if an injury occurs, to be positive so as to mitigate moral-hazard and mis-reporting problems. The uncompensated loss to the firm of a defective product is $L_F \geq 0$. The total loss caused by a defective product is $L \equiv L_F + L_C$, where L is allocated between the firm and consumer by the liability system (see Cooter, 1991; Kaplow and Shavell, 1999 for discussions of various allocation systems). This allocation is also treated as being exogenously determined.

The per unit cost of production is assumed to be $C(\theta) = c(1 - \alpha\theta)$, where $c > 0$ and $\alpha \in [0, 1]$, c is the marginal cost of producing a product without defect, and α is a parameter that reflects the degree to which quality influences per unit cost. Naturally, a safer product is more costly to produce $\partial C/\partial\theta = -\alpha c < 0$. The firm's *total* marginal cost (including liability costs) is $TMC = c(1 - \alpha\theta) + \theta L_F$ as each unit is produced at a cost of $c(1 - \alpha\theta)$ and generates a loss of L_F with probability θ. The firm's marginal cost of product risk per unit is $\partial TMC/\partial\theta = L_F - \alpha c$. Given these two marginal costs of product risk, the degree to which marginal cost changes with quality, the orientation of the liability system can be characterized as follows: if $L_F - \alpha c > (<) L_C$, the liability system is said to be consumer (firm)-oriented, since the firm (consumer) pays for the damage more than the consumer (firm). If $L_F - \alpha c = L_C$, then the system is said to be neutral.

3. No hidden information and no hidden action

In this world, the consumer is able to observe both product quality, θ, and the amount of R&D, x, and then chooses the quantity of consumption to maximize utility subject to a budget constraint that accounts for the consumer's expected liability costs when the product is defective. The utility function U of a representative consumer is assumed to be

$$U(q, z) = q\left(\frac{a}{b}\right) - \frac{q^2}{2b} + z, \tag{1}$$

where q is the quantity of the good consumed and z is the quantity of the numéraire good consumed, respectively. The market demand function is derived as that of the representative consumer endowed with an initial holding of the numéraire good $\bar{z}$ and total profit income of the economy, M. The consumer's budget constraint is

$$pq + \theta L_C q + z = \bar{z} + M, \tag{2}$$

where p is the price of the product[2]. Solving the consumer's utility maximization problem for a given θ gives

$$q = a - b(p + \theta L_C). \tag{3}$$

[2] Here, the consumer suffers when product quality is low due to the cost of injuries caused by the product. Another way to specify the problem would be to assume that product defects lower utility, but because the utility function is quasi-linear, the two approaches yield identical results.

The monopolist's profit function at the second stage is

$$\Pi^{\mathrm{I}}(p,\theta,x) = [a - b(p + \theta L_{\mathrm{C}})][p - c(1 - \alpha\theta) - \theta L_{\mathrm{F}} + \beta x] - \gamma x^2, \tag{4}$$

where the superscript I indicates that the consumer is informed. Since R&D is assumed to be of the cost-reducing type, that is, the firm is able to reduce costs by $\beta > 0$ per unit of R&D, so that β is the benefit of conducting R&D. The cost of R&D, γx^2, is assumed to be quadratic in x, reflecting the existence of diminishing returns to R&D expenditures. The profit function depends on product price, product quality and the amount of R&D. The equilibrium price depends on product quality, the amount of R&D, and the liability system.

Assumption 1. $4\gamma - b\beta^2 > 0$. Assumption 1 ensures that the second order condition for profit maximization with respect to R&D, x, with no hidden information and no hidden action is satisfied.

Proposition 1.

(a) *Price decreases as R&D increases regardless of the firm's marginal cost of product risk per unit.*
(b) *Given* Assumption 1, *if* $L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}$ *is positive (negative), then R&D decreases (increases) as quality worsens.*
(c) *Given* Assumption 1, *if* $L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}}$ *is positive (negative and for sufficiently large* γ*), then price increases (decreases) as quality worsens.*

Proof.

(a) Let $A = a/b$ in what follows. The equilibrium price is

$$p^{\mathrm{I}}(\theta,x) = \tfrac{1}{2}[A + \theta(L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}}) + c - \beta x]. \tag{5}$$

If the amount of R&D increases, the equilibrium price will fall

$$\frac{\partial p^{\mathrm{I}}}{\partial x} = -\frac{\beta}{2} < 0. \tag{6}$$

Regardless of the firm's marginal cost of product risk per unit, an increase in the amount of R&D causes the price to decline. The degree of the change in prices is half the benefit arising from the increased R&D.

(b) At the first stage, the amount of R&D which maximizes profits is

$$x^{\mathrm{I}} = \frac{b\beta[A - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - c]}{4\gamma - b\beta^2}. \tag{7}$$

Product quality will influence the amount of R&D, as a change in product quality affects R&D as follows

$$\frac{\partial x^{\mathrm{I}}}{\partial \theta} = \frac{-b\beta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})}{4\gamma - b\beta^2}. \tag{8}$$

Given Assumption 1, the sign of $\partial x^{\mathrm{I}}/\partial\theta$ is determined by the sign of $L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}$.

(c) Given (5) and (7), the impact of a change in quality on price is given by

$$\frac{\partial p^{\mathrm{I}}}{\partial \theta} = \frac{2\gamma(L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}}) + b\beta^2 L_{\mathrm{C}}}{4\gamma - b\beta^2}. \tag{9}$$

If $L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}} > 0$, price increases as quality worsens. When γ is sufficiently large, that is, R&D is relatively expensive, if $L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}} < 0$, price decreases as quality worsens. □

The key insight of Proposition 1 is that when the marginal cost including both production cost and product liability costs per unit is higher for lower quality goods, a monopolist signals high quality by selecting a lower price. The lower price demonstrates the monopolist's willingness to tolerate high volume. Given that such a monopolist will have high volume, it will be attracted to greater investment in (per-unit) cost reduction.

4. Prices and the amount of R&D as signals

This section considers the case where the consumer is unable to observe product quality, but is able to observe price and the amount of R&D. When the firm's R&D activities are observable, R&D also serves as a signal of product quality. As a result, both the product price and the amount of R&D are signals of product quality.

The timing in the R&D stage is as follows: The firm conducts an amount of cost-reducing R&D and supplies a product with an exogenously determined θ. The consumer forms a belief about product quality $\Theta^C(\cdot,\cdot)(p,x)\mapsto\theta$, that is based on the observable p and x. For simplicity and for ease of calculation, a linear belief function is assumed (see Appendix A)[3]. The firm chooses p to maximize $\Pi(p,\theta,\Theta(p,x))$, given θ, $\Theta(\cdot,\cdot)$, and x.

We search for an equilibrium where each θ is associated with a different p given x. Hence, the equilibrium price function $p^*(\cdot,\cdot) : (\theta,x)\mapsto p$ can be transformed to the function $\Theta(\cdot,\cdot)(p,x)\mapsto\theta$. In equilibrium, the consumer's belief is said to be consistent if $\Theta^C(p,x) = \Theta(p,x) = \theta$.

The profit function for the monopolist at the second stage is

$$\begin{aligned} &\Pi^{\mathrm{U}}(p(\theta,x),\Theta(p(\theta,x),x),\theta,x) \\ &\quad = [a - b(p + \Theta(p,x)L_{\mathrm{C}})][p - c - \theta(L_{\mathrm{F}} - \alpha c) + \beta x] - \gamma x^2. \end{aligned} \tag{10}$$

The superscript U indicates hidden information, that is, the consumer is uninformed about product quality. The profit function depends on the consumer's belief, price, product quality, and the amount of R&D. Although, in general, the belief Θ would be a non-linear function of price and the amount of R&D, here to provide a benchmark case, it is assumed the belief is a linear function of price and the amount of R&D. To satisfy the boundary condition, namely, that the firm with the worst quality ($\theta = 1$) does not distort its price, it is assumed

[3] Although it would involve more complicated calculations, it is expected that similar results would be obtained even if the belief function were assumed to be an increasing non-linear function of x and p.

Assumption 2.

$$A - c - \theta(L_F - \alpha c + L_C) = 0 \ \text{ if } \theta = 1,$$
$$A - c - \theta(L_F - \alpha c + L_C) > 0 \ \text{ for } \theta < 1.$$

Assumption 2 ensures that the price with the worst quality coincides across information structures, since the consumer have knowledge of the price with the worst quality. That is, Assumption 2 ensures that the price distortion does not occur when the product must be defective ($\theta = 1$).

Assumption 3.

$$4\gamma(L_F - \alpha c + L_C)^2 - b\beta^2(L_F - \alpha c)(L_F - \alpha c + 2L_C) > 0.$$

Assumption 3 ensures that the second order condition for profit maximization with respect to R&D, x, with hidden information is satisfied.

Assumption 4. $L_F - \alpha c + 2L_C$ and $L_F - \alpha c$ have the same sign.Assumption 4 ensures that the second order condition for profit maximization with respect to price, p, with hidden information is satisfied.

Proposition 2.

(a) *Given* Assumption 4, *price decreases as R&D increases regardless of the firm's marginal cost of product risk per unit.*
(b) *Given* Assumption 3, *if the firm's marginal cost of product risk per unit* $(L_F - \alpha c)$ *is positive* (*negative*), *then a large* (*small*) *amount of R&D and a low (high) price signal high quality.*

Proof.

(a) The price with hidden information is

$$p^U = \frac{A - \delta L_C}{2(1 + \mu L_C)} + \frac{1}{2}(c + \theta(L_F - \alpha c) - \beta x), \tag{11}$$

where δ and μ are defined in Appendix A that derives an explicit expression for the belief, $\Theta(p, x)$. A change in the amount of R&D affects the price as follows

$$\frac{\partial p^U}{\partial x} = \frac{-\beta(L_F - \alpha c + 2L_C)}{2(L_F - \alpha c + L_C)} < 0. \tag{12}$$

An increase in the amount of R&D causes the product price to fall regardless of the firm's marginal cost of product risk per unit. With no hidden information and action, the fall in product price is exactly half of the benefit from R&D, β, whereas with hidden information, the fall is greater than half of the benefit from R&D, since $(L_F - \alpha c + 2L_C)/(L_F - \alpha c + L_C) > 1$.

(b) At the first stage, we are interested in whether the amount of R&D can signal product quality, and will be looking for a revealing equilibrium, in which each θ is associated with a different equilibrium amount of R&D. The impact of a change in quality on equilibrium R&D is given by

$$\frac{\partial x^{\mathrm{U}}}{\partial \theta} = \frac{-b\beta(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})}{4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2 - b\beta^2(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})}. \tag{13}$$

If the firm's marginal cost of product risk per unit is positive (negative), the amount of R&D decreases (increases) as quality worsens.

The impact of a change in quality on the marginal profit of R&D is given by

$$\frac{\partial}{\partial \theta}\left(\frac{\partial \Pi}{\partial x}\right) = \frac{-b\beta(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})}{2(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})}. \tag{14}$$

If the firm's marginal cost of product risk per unit is positive (negative), this expression is negative (positive). The effect of a change in quality on equilibrium R&D is presented in Fig. 1.

The firm conducts less R&D for a product with poor quality when $L_{\mathrm{F}} - \alpha c$ is positive. It seems that the firm has less incentive to undertake R&D, since the firm has lower profits when the product quality is poor. On the other hand, the firm conducts more R&D for a poor quality product when $L_{\mathrm{F}} - \alpha c$ is negative. It seems that the firm has an incentive to conduct R&D, since the firm enjoys higher profits when the product quality is poor.

The effect of change in quality on the price is

$$\frac{\partial p}{\partial \theta}(\theta, x(\theta)) = \frac{\partial p}{\partial \theta} + \frac{\partial p}{\partial x}\frac{\partial x}{\partial \theta}. \tag{15}$$

If $L_{\mathrm{F}} - \alpha c$ is positive (negative), then

$$\frac{\partial p}{\partial \theta} > (<)0, \quad \frac{\partial p}{\partial x} < 0 \quad \text{and} \quad \frac{\partial x}{\partial \theta} < (>)0.$$

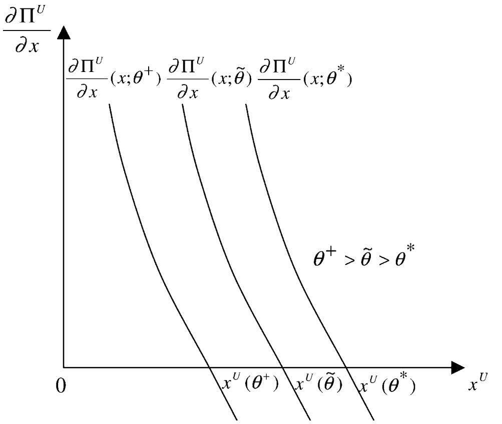

Fig. 1. Effect of a change in quality on equilibrium R&D with hidden information ($L_{\mathrm{F}} - \alpha c > 0$).

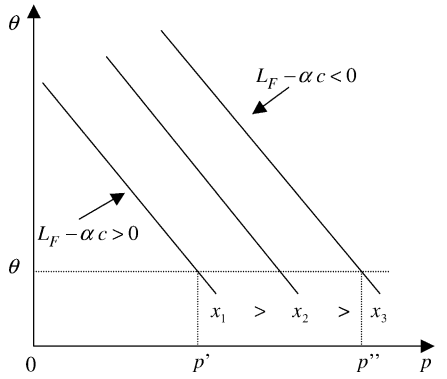

Fig. 2. Price and R&D signal product quality.

Hence,

$$\frac{\partial p}{\partial \theta}(\theta) > (<)0. \qquad \square$$

Since the firm knows the product quality, the consumer is able to perceive the product quality by observing both the amount of R&D and price. Each quality is associated with a different equilibrium amount of R&D and price. The relationship between these variables is depicted in Fig. 2. In Fig. 2, for a given x, say x_1, there is a relationship between θ and p. Similarly for a given p, there is a relationship between θ and x. That is, in this situation, both the price and R&D signal product quality. For example, to signal the product quality is θ' (high quality) in Fig. 2, when $L_F - \alpha c$ is positive, the firm sets the pair p' and x_1 (low price and a large amount of R&D). When $L_F - \alpha c$ is negative, the firm sets the pair p'' and x_3 (high price and small amount of R&D).

In this model, the liability cost to consumers is incurred with greater probability when quality is lower, but consumers do not observe product quality. So, as in the standard signaling model, they must form beliefs about product quality, preferring to buy a higher-quality good at any given market price, p. The expected liability expenditure ends up functioning like a vertical-differentiation measure of the expected quality of the product.

When marginal cost (inclusive of liability costs) is higher for lower-quality goods, the monopolist signals higher quality by lowering its price, demonstrating its willingness to expand volume. A higher R&D level is complementary to this process, since greater (cost-reducing) R&D is more attractive when volume is higher. On the other hand, when the marginal cost (inclusive of liability costs) is higher for higher-quality goods, then the monopolist signals higher quality by raising its price, demonstrating its willingness to decrease volume. A lower R&D level is complementary to this process, since less (cost-reducing) R&D is more attractive when volume is lower. This volume effect can also be observed in Bagwell's (1991) model of a monopolistic exporter. Under the assumption that marginal cost is higher when product quality is higher, Bagwell (1991) shows that the high-quality monopolist signals with a high price, reducing its volume. The low-quality monopolist has higher sales volume and thus receives the greatest benefit from a per-unit export subsidy (which reduces products cost, just like R&D).

5. Hidden information and hidden action

This subsection examines the case where the firm conducts unobservable cost-reducing R&D, so price is the only observable variable for the consumer. The consumer perceives product quality by observing only prices.

The profit function for the monopolist at the second stage is

$$\begin{aligned}&\Pi^0(p(\theta,x),\Theta(p(\theta,x)),\theta,x)\\&\quad=[a-b(p+\Theta(p)L_C)][p-c-\theta(L_F-\alpha c)+\beta x]-\gamma x^2. \qquad (16)\end{aligned}$$

The superscript 0 indicates that the consumer has knowledge of neither information nor action. The right hand sides of Eqs. (10) and (16)are identical. However, since the consumer cannot observe the amount of R&D, the way the consumer forms his/her belief about quality will differ from the hidden information case. The profit function depends on the consumer's belief, price, product quality and the amount of R&D.

The consumer's belief with hidden information and hidden action can be solved in an analogous way to the hidden information case explained in Appendix A. The difference is that the R&D, x, is not an observable variable so that the belief only depends on price. Price is the only signal of product quality; a low (high) price signals high quality when the firm's marginal cost of product risk is positive (negative).

The firm maximizes its profits as in the case where R&D is observable. The difference between the observable R&D case and the unobservable R&D case is the amount of R&D the firm conducts.

Assumption 5.

$$4\gamma(L_F-\alpha c+L_C)-b\beta^2(L_F-\alpha c+2L_C)>0$$

Assumption 5 ensures that the second order condition for profit maximization with respect to R&D, x, with hidden information and hidden action is satisfied.

Proposition 3. *Given* Assumptions 4 and 5, *the amount of R&D decreases as product quality worsens regardless of the firm's marginal cost of product risk per unit.*

Proof. The amount of R&D which maximizes profits is

$$x^0=\frac{b\beta(A-c-\theta(L_F-\alpha c+L_C))(L_F-\alpha c+2L_C)}{4\gamma(L_F-\alpha c+L_C)-b\beta^2(L_F-\alpha c+2L_C)}. \qquad (17)$$

Product quality will affect the amount of R&D, and the impact of a change in quality on R&D is given by

$$\frac{\partial x^0}{\partial\theta}=\frac{-b\beta(L_F-\alpha c+L_C)(L_F-\alpha c+2L_C)}{4\gamma(L_F-\alpha c+L_C)-b\beta^2(L_F-\alpha c+2L_C)}<0. \qquad \square \qquad (18)$$

Proposition 4. *In the three cases of no hidden information and no hidden action (I), hidden information and no hidden action (U), and hidden information and hidden action (0), the ranking of the amount of R&D is* $x^0 \geq x^{\mathrm{I}} \geq x^{\mathrm{U}}$.

Proof. The amount of R&D with hidden information and hidden action in (17) is, larger than one with no hidden information and no hidden action in (7), since

$$x^0 - x^{\mathrm{I}} = \frac{4b\beta\gamma L_{\mathrm{C}}(A - c - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}))}{(4\gamma - b\beta^2)[4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - b\beta^2(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]} \geq 0, \tag{19}$$

Assumptions 1 and 5 ensure the denominator is positive. The amount of R&D with hidden information is

$$x^{\mathrm{U}} = \frac{b\beta(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})(A - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - c)}{4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2 - b\beta^2(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})}. \tag{20}$$

The amount of R&D with no hidden information and no hidden action is larger than one with hidden information, since

$$x^{\mathrm{I}} - x^{\mathrm{U}} = \frac{4b\beta\gamma(L_{\mathrm{C}})^2(A - c - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}))}{(4\gamma - b\beta^2)[4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2 - b\beta^2(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]} \geq 0. \quad \square \tag{21}$$

Unlike the two previous cases (the no hidden information and no hidden action case and the hidden information and no hidden action case), the amount of R&D is unobservable here and does not serve as a signal that depends on marginal costs (inclusive of liability costs). Thus, regardless of marginal costs (inclusive of liability costs), the firm here tries to conduct more R&D when the product is high quality to lower the increasing costs associated with the improvement of quality.

The result of Proposition 4 may be derived from the price distortion as a consequence of product quality signaling. This price distortion is examined in Appendix B. The amount of investment in each case is selected so as to meet the profit maximizing price. Hence, the firm conducts the most investment and the price is always the lowest in the hidden information and hidden action case.

6. The effect of liability costs on R&D

This section explores how changes in the distribution of liability costs affects the firm's R&D decisions with the three different information structures.

Viscusi and Moore's (1993) theoretical model predicts that an increase in liability costs has a positive impact on the firm's R&D decision, but this contradicted by their empirical results which find that increases in product liability have a statistically significant negative impact on R&D. This paper provides one theoretical foundation for Viscusi and Moore's (1993) observed empirical regularity.

Proposition 5. *When the firm's liability costs increase, the amount of R&D*

(a) *is not affected with no hidden information and no hidden action*;
(b) *increases with hidden information for* $\theta < 1$; *and*
(c) *decreases* (*increases*) *with hidden information and hidden action when* $L_F - \alpha c > (<)\, 0$ for $\theta < 1$.

Proof.

(a) The amount of R&D with no hidden information and no hidden action is

$$x^{I} = \frac{b\beta[A - \theta(L_F - \alpha c + L_C) - c]}{4\gamma - b\beta^2} = \frac{b\beta[A - \theta(L - \alpha c) - c]}{4\gamma - b\beta^2}. \tag{22}$$

As a result, it is obvious that changes in the product liability system have no impact on the firm's R&D decision:

$$\left.\frac{\partial x^{I}}{\partial L_F}\right|_{L=\text{constant}} = 0. \tag{23}$$

(b) The amount of R&D with hidden information is given by (20). The impact of a shift in liability from the consumer to the firm is given by

$$\left.\frac{\partial x^{U}}{\partial L_F}\right|_{L=\text{constant}} = \frac{8b\beta\gamma L_C (L - \alpha c)^2 (A - \theta(L - \alpha c) - c)}{[4\gamma(L - \alpha c)^2 - b\beta^2 (L_F - \alpha c)(2L - \alpha c - L_F)]^2} \geq 0. \tag{24}$$

That is, as product liability costs increase, the firm increases the amount of R&D. At the point of worst quality, $\theta = 1$, the product liability system has no impact on the firm's decision, since the R&D level with hidden information coincides with one with no hidden information and no hidden action in this case.

(c) The amount of R&D with hidden information and hidden action is given by (17). The impact of a change in the liability system is given by

$$\left.\frac{\partial x^{0}}{\partial L_F}\right|_{L=\text{constant}} = \frac{-4b\beta\gamma(L - \alpha c)(A - c - \theta(L_F - \alpha c + L_C))}{[4\gamma(L_F - \alpha c + L_C) - b\beta^2 (L_F - \alpha c + 2L_C)]^2} \leq (\geq) 0$$
$$\Leftrightarrow L_F - \alpha c > (<) 0. \tag{25}$$

When $L_F - \alpha c$ is negative (positive), the firm increases (decreases) the amount of R&D as product liability costs increase. At the point of worst quality, the product liability system has no impact on the firm's decision. □

The Coase theorem is often raised in discussions of product liability problems (see Coase, 1960). In his original paper, Coase asserted that "the ultimate result (which maximizes the value of production) is independent of the legal position if the pricing system is assumed to work without cost" (p. 8). While the Coase theorem and its assumptions have been interpreted in many ways, the standard assumptions for the Coase theorem to hold are, in general, the absence of transaction costs, the perfect endowment of rights, and complete information (see, for example, Farrell, 1987; Hurwicz, 1995). The model with no hidden information and no hidden action satisfies those three standard assumptions, and proves that changes in the liability allocation system between the firm and the consumers have no impact on the firm's R&D decision.

Since Viscusi and Moore's (1993) theoretical model does not distinguish between an increase in society's liability costs (L) and a reallocation of liability costs between consumers and the firm, their results which suggests an increase in product liability costs decreases R&D can also be interpreted in this model as the impact of change in the costs to society of a defective product on R&D spending, namely,

$$\frac{\partial x^{\mathrm{I}}}{\partial L} = \frac{-b\beta\theta}{4\gamma - b\beta^2} < 0, \tag{26}$$

given Assumption 1.

The results of the model with hidden information (Eq. (24)) is also consistent with the empirical results of Viscusi and Moore (1993). Their analysis shows that product liability costs have a significant positive impact on the firm's R&D decision, since at the sample mean, Viscusi and Moore (1993) find that liability costs increase R&D intensity by 15 percent. An increase in firm's liability costs entails an increase of firm's costs, therefore the firm conducts more R&D. At the point of worst quality ($\theta = 1$), the price with hidden information coincides with the price with no hidden information and no hidden action. As a result, at that point the liability system has no impact on the firm's R&D decision.

In the model with hidden information and hidden action, the firm's R&D decision depends on the firm's marginal cost of product risk ($L_{\mathrm{F}} - \alpha c$). When the firm's liability costs (L_{F}) increase, the gap between the marginal cost for a firm with high quality product and for a firm with low quality product widens. When $L_{\mathrm{F}} - \alpha c$ is positive (negative), the firm does not need to lower (higher) price to prevent mimicry by its other types of products as L_{F} increases. Therefore, an increase in the firm's liability costs makes the firm conduct less (more) R&D when $L_{\mathrm{F}} - \alpha c$ is positive (negative). At the point of worst quality ($\theta = 1$), the liability system has no impact on the firm's R&D decision.

7. Incentive for information revelation

Suppose that there is a stage zero where the firm chooses whether to make its private information public or to keep it private is appended before stage one. This section examines whether the firm has an incentive to reveal information on product quality to the consumer in such a model [4]. With hidden information, the firm knows the product's quality, but the

[4] This paper does not consider explicitly the case where the firm intentionally publishes false information about product quality and the amount of R&D. In the United States, the release of false information about product quality by a firm is prohibited by various acts including the Unfair Competition and Unfair Trade Practices Act. In Japan, Article 19 of the Anti-Trust Law (Dokusen kinshi ho) provides a similar prohibition. In effect, in the English case *Carlill versus Carbolic Smoke Ball Co.* (1893, 1 QB 256), the plaintiff successfully obtained a civil damages award when the information about quality the firm offered was shown to be partially false. In Japan, false reporting of R&D expenditure is also prohibited by Article 260 of the National Tax Law (Credit for Experimental and Research Expenses) and Articles 11 and 24 of the Securities and Exchange Act (Shoken torihiki ho) relating to the Securities and Exchange Surveillance Commission (SESC). In the United States, false reporting of R&D is prohibited in many ways including by the Securities and Exchange Commission Act. Therefore, once a firm makes information about product quality and R&D public, it must be true. An additional verifiable act is thus not necessary in this paper.

consumer does not. If the profits of the monopolist increase when the consumer knows the quality, then the firm has an incentive to reveal its information on product quality. For instance, the firm can release to the public any experimental evidence it has relating to quality. If the profits of the monopolist with hidden information are greater than when the consumer is fully informed, then the firm has an incentive to conceal information on product quality.

Proposition 6. *The monopolist has an incentive to reveal information on product quality and R&D to the consumer.*

Proof. The firm's profit with no hidden information and no hidden action is

$$\Pi^{\mathrm{I}}(\theta) = \frac{\mathrm{NUM}^{\mathrm{I}}}{\mathrm{DEN}^{\mathrm{I}}}, \tag{27}$$

where $NUM^{\mathrm{I}} = b\gamma[A - c - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})]^2$ and $\mathrm{DEN}^{\mathrm{I}} = 4\gamma - b\beta^2$. The firm's profit with hidden information is

$$\Pi^{\mathrm{U}}(\theta) = \frac{\mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})}{\mathrm{DEN}^{\mathrm{U}}}, \tag{28}$$

where $\mathrm{DEN}^{\mathrm{U}} = 4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2 - b\beta^2(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})$. The firm's profit with hidden information and hidden action is

$$\Pi^{0}(\theta) = \frac{\mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})[4\gamma(L_{\mathrm{F}} - \alpha c) - b\beta^2(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]}{\mathrm{DEN}^{0}}, \tag{29}$$

where $\mathrm{DEN}^{0} = [4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - b\beta^2(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]^2$. The profit with no hidden information and no hidden action is greater than or equal to that with hidden information, since

$$\Pi^{\mathrm{I}}(\theta) - \Pi^{\mathrm{U}}(\theta) = \frac{4\gamma(L_{\mathrm{C}})^2\mathrm{NUM}^{\mathrm{I}}}{(\mathrm{DEN}^{\mathrm{I}})(\mathrm{DEN}^{\mathrm{U}})} \geq 0. \tag{30}$$

Equality holds only when $\theta = 1$. The profit with hidden information is greater than or equal to that with hidden information and hidden action since

$$\Pi^{\mathrm{U}}(\theta) - \Pi^{0}(\theta) = \frac{\mathrm{NUM}^{\mathrm{I}}[(2\beta L_{\mathrm{C}})(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]^2}{(\mathrm{DEN}^{\mathrm{U}})(\mathrm{DEN}^{0})} \geq 0. \tag{31}$$

Again equality holds only when $\theta = 1$. Thus, the ordering of profits is $\Pi^{\mathrm{I}} \geq \Pi^{\mathrm{U}} \geq \Pi^{0}$. □

As a result, the firm has an incentive to make information on product quality and R&D available to the public, that is, there is an incentive for information revelation. Even if product quality is difficult for the consumer to evaluate, for example, when a new product or new technology is used, the firm will try to reveal all the information it has on quality to overcome the information gap.

The existing literature has already shown that the market provides incentives for informed sellers to disclose information when there are many sellers (for example, Stiglitz, 1975).

It has also been shown that the argument is similar even if the seller is a monopolist (see Matthews and Postlewaite, 1985). Proposition 6 means that this argument holds even when the model is extended to include additional private information about R&D, the R&D investment stage and the product liability costs.

The firm has lower profits with hidden information, since the firm does not charge the optimal price for the actual quality. It distorts its price and profits. This price distortion is examined in Appendix B. As Appendix B shows, when the firm's marginal cost of product risk per unit is positive, the ranking of prices in the three information cases are as follows: $p^0 \leq p^U \leq p^I$. When the consumer does not know the quality, the firm sets a higher price in order to prevent mimicry. The firm with a low quality product would mimic the price of a firm with high quality product, and this makes the firm with a high quality product set an even lower price, so as to signal that it is not a low quality firm. The distortion occurs as a consequence of product quality signaling. If the firm's marginal cost of product risk per unit is negative, $L_F - \alpha c < 0$, then the price with hidden information is higher in order to suggest a product of high quality.

When the firm's marginal cost of product risk per unit is positive, the less information the consumer has on quality, the lower the price becomes. This means the distortion is greater when there is less information in the market. Therefore, the firm is worse off with hidden information because of the nature of the distortion to prevent mimicry.

8. Welfare analysis

This section examines the socially optimal amount of R&D and compares the social welfare levels with the three information structures.

Let social welfare be the sum of consumer surplus and producer surplus (profits).

Assumption 6.

$$8\gamma(L_F - \alpha c + L_C)^2 - 3b\beta^2(L_F - \alpha c)(L_F - \alpha c + 2L_C) > 0$$

Assumption 6 ensures that the second order condition for social welfare maximization with respect to R&D, x, with hidden information is satisfied.

Proposition 7. *Given Assumption 6, the firm's profit and social welfare with nothing hidden are higher than or equal to the firm's profit and social welfare with hidden information and with hidden information and hidden action.*

Proof. The amount of R&D which maximizes social welfare with hidden information is

$$x^{U*} = \frac{3b\beta(L_F - \alpha c)(L_F - \alpha c + 2L_C)(A - \theta(L_F - \alpha c + L_C) - c)}{8\gamma(L_F - \alpha c + L_C)^2 - 3b\beta^2(L_F - \alpha c)(L_F - \alpha c + 2L_C)}, \quad (32)$$

and this is positive given Assumption 6. The amount of R&D which maximizes profits with hidden information is given by (20). The amount of R&D the firm conducts is smaller than the socially optimal level regardless of the firm's marginal cost of product risk per unit. As in the hidden information case, the equilibrium amount of R&D is smaller than the socially optimal level in both the case with nothing hidden and with hidden information and hidden action.

Consumer surplus with no hidden information and no hidden action is

$$\mathrm{CS}^{\mathrm{I}}(\theta) = \frac{2\gamma \mathrm{NUM}^{\mathrm{I}}}{\mathrm{DEN}^{\mathrm{I}}}. \tag{33}$$

Consumer surplus with hidden information is

$$\mathrm{CS}^{\mathrm{U}}(\theta) = \frac{2\gamma \mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2}{\mathrm{DEN}^{\mathrm{U}}}. \tag{34}$$

Consumer surplus with hidden information and hidden action is

$$\mathrm{CS}^{0}(\theta) = \frac{2\gamma \mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})}{\mathrm{DEN}^{0}}. \tag{35}$$

The ordering of these consumer surpluses is $\mathrm{CS}^{\mathrm{I}} \geq \mathrm{CS}^{0} \geq \mathrm{CS}^{\mathrm{U}}$.

To examine the effect of information structures on social welfare, the level of social welfare with no hidden information and action and with hidden information are compared

$$W^{\mathrm{I}} = \frac{\mathrm{NUM}^{\mathrm{I}}(6\gamma - b\beta^2)}{\mathrm{DEN}^{\mathrm{I}}} \tag{36}$$

$$W^{\mathrm{U}} = \frac{\mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})[6\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2 - b\beta^2(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]}{\mathrm{DEN}^{\mathrm{U}}} \tag{37}$$

Social welfare with hidden information and hidden action is

$$W^{0} = \frac{\mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})[6\gamma(L_{\mathrm{F}} - \alpha c) - b\beta^2(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})]}{\mathrm{DEN}^{0}}. \tag{38}$$

The firm's profit and consumer surplus with no hidden information and no hidden action both are the highest of the three information cases, so social welfare is highest with no hidden information and no hidden action ($W^{\mathrm{I}}(\theta)$). The relationship between the remaining two levels of social welfare is

$$\begin{aligned} &W^{\mathrm{U}}(\theta) - W^{0}(\theta) \\ &\quad = \frac{-2b\beta^2\gamma L_{\mathrm{C}}\mathrm{NUM}^{\mathrm{I}}(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})^2}{(\mathrm{DENO}^{\mathrm{U}})(\mathrm{DENO}^{0})} \times [8\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})^2(L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}}) \\ &\qquad - b\beta^2(L_{\mathrm{F}} - \alpha c)(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})(2L_{\mathrm{F}} - 10\alpha c - L_{\mathrm{C}})]. \end{aligned} \tag{39}$$

If $L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}} > (<)0$, then $W^{\mathrm{U}} \leq (\geq) W^{0}$, since profits with hidden information are greater than with hidden information and hidden action, and the consumer surplus with hidden information and hidden action is greater than with hidden information.

The comparison of R&D levels found that the amount of R&D is smaller than the socially optimal level under any information structure. This is due to not so much to the information structure, but rather it is due to the assumed monopoly market structure. The comparison of social welfare levels found that social welfare with no hidden information and no hidden action is higher than with hidden information and with hidden information and hidden action. The ordering of consumer surpluses and profits are, $\mathrm{CS}^{\mathrm{I}} \geq \mathrm{CS}^{0} \geq \mathrm{CS}^{\mathrm{U}}$ and $\Pi^{\mathrm{I}} \geq \Pi^{\mathrm{U}} \geq \Pi^{0}$. If the liability system is consumer-oriented, then the ordering of social welfare is $W^{\mathrm{I}} \geq W^{0} \geq W^{\mathrm{U}}$, and if the liability system is firm-oriented, then the ordering of social welfare is $W^{\mathrm{I}} \geq W^{\mathrm{U}} \geq W^{0}$. □

The monopolist in the asymmetric information case can attain the same profit level as in the full information case only when quality is worst. In all other cases, the monopolist's profit level will be lower in the asymmetric information because the firm is not charging the optimal price corresponding to observable quality. Turning to a comparison of consumer surplus, the ordering of the price level depends on whether marginal cost is positive or negative (see Appendix B), but consumer surplus is always higher in the full information case than in the asymmetric information case because, even though price is sometimes lower in the asymmetric information case than in the full information case, consumer surplus is still lower because the demand function is different in the two cases. Thus, both the firm's profit, consumer surplus, and hence social welfare will always be higher in the full information case than in the asymmetric information case.

9. Concluding remarks

The effects of product liability costs on the firm's R&D decision differs among the information structures. When the consumer is fully aware of product quality, changes in product liability have no impact on firm's decisions as the Coase theorem suggests. When the consumer does not have full information, changes in product liability have an impact. It is shown that an increase in the firm's liability costs promotes the firm's R&D with hidden information. With hidden information, changes in policy concerning product liability allocation have impact on the firm's R&D decisions.

The implications of this paper for the impact of changes in the distribution of liability costs on the level of R&D as a result of the implementation of the Product Liability Law in Japan in 1994 are investigated in Takaoka (2002). Empirical evidence of Takaoka (2002) is consistent with the Proposition 5(b).

The findings shown here suggest that in order to increase social welfare, a policy to promote the firm's R&D closer to the socially optimal level is necessary under each information structure. The level of R&D is lower than the social optimum level due to the monopoly enjoyed by the firm, rather than the information structure. The monopoly price is high and a lower amount of R&D is conducted by the monopolist.

Although product quality is chosen exogeneously in this paper, the model could be extended to the case where R&D explicitly affects product quality so that quality would be chosen endogenously. Another natural extension is to introduce competition by increasing the number of firms. Suppose competition forces one firm to set a lower price and conduct more R&D, then this may change the policy recommendation concerning information revelation.

Acknowledgements

The author would like to thank Colin McKenzie and Ken-Ichi Shimomura for valuable comments during various stages of the preparation of this paper, and Charles Yuji Horioka, Koji Ishibashi, Shingo Ishiguro, and Hideshi Itoh for their helpful suggestions. The comments of an anonymous referee have led to a significant improvement in the quality and understandability of the paper. An earlier version of this paper was presented at the spring conference of the Japanese Economic Association held at Yokohama City University, May 2000.

Appendix A. Consumer beliefs with hidden information

In this appendix, an analytic expression for the consumer's belief is derived and the belief is shown to be unique.

In equilibrium, consistency of beliefs requires $\Theta^*(p(\theta), x) = \theta$. Assume the belief has the following form

$$\Theta^*(p(\theta, x), x) = \theta = \delta_0 + \delta_1 x + \mu p \quad (L_F - \alpha c \neq 0), \tag{A.1}$$

where μ is a positive number.

Substituting (A.1) into the first order condition for profit maximization gives

$$p[(1 + \mu L_C)(2 - \mu(L_F - \alpha c))] - (1 + \mu L_C)[c + \delta(L_F - \alpha c) - \beta x] - A + \delta L_C = 0. \tag{A.2}$$

The values of μ that satisfy this condition are

$$\mu = -\frac{1}{L_C}, \frac{2}{L_F - \alpha c}.$$

For the second order condition for profit maximization with respect to price to be satisfied with hidden information requires

$$\frac{\partial^2 \Pi^U}{\partial p^2} = -2b(1 + \mu L_C) < 0. \tag{A.3}$$

For (A.3) to be satisfied requires $(1 + \mu L_C) > 0$. Hence, $\mu = 2/(L_F - \alpha c)$ is the only feasible solution. Substituting $\mu = 2/(L_F - \alpha c)$ into the second order condition gives

$$-2b(1 + \mu L_C) = -2b\left(\frac{L_F - \alpha c + 2L_C}{L_F - \alpha c}\right) < 0. \tag{A.4}$$

Hence, $L_F - \alpha c + 2L_C$ and $L_F - \alpha c$ must have the same sign.

As a result, the belief in (A.1) shows that consumers perceive that a high (low) price signals low quality if $L_F - \alpha c$ (and thus μ) is positive (negative). An increase (decrease) in price makes the consumer perceive a fall in the quality, if $L_F - \alpha c$ is positive (negative). The degree of the consumer's perception depends on the firm's marginal cost of product risk per unit:

$$\Theta^*(p(\theta, x), x) = \frac{A(L_F - \alpha c) - c(L_F - \alpha c + 2L_C) + \beta x(L_F - \alpha c + 2L_C)}{(L_F - \alpha c)(L_F - \alpha c + L_C)} + \frac{2}{L_F - \alpha c} p. \tag{A.5}$$

The second order condition for profit maximization shows that $L_F - \alpha c$ and $L_F - \alpha c + 2L_C$ always have the same sign.

The belief shows that the consumer perceives that a higher (lower) price signals lower quality and a larger (smaller) amount of R&D signals lower quality if $L_F - \alpha c$ is positive (negative).

A.1. Uniqueness

The unique solution of the linear function is $\mu = 2/(L_F - \alpha c)$. By the first order condition for profit maximization,

$$\frac{\partial \Theta(p)}{\partial p} = \frac{A - p - \theta L_C}{L_C(p - c - \theta(L_F - \alpha c) + \beta x)} - \frac{1}{L_C}. \tag{A.6}$$

Since the monopolist produces only when profits are positive,

$$\begin{aligned} &A - p - \theta L_C > 0 \Rightarrow \theta < \frac{A - p}{L_C}, \\ &p - c - \theta(L_F - \alpha c) + \beta x > 0 \Rightarrow \theta < \frac{p - c + \beta x}{L_F - \alpha c}. \end{aligned} \tag{A.7}$$

Suppose that the firm's marginal cost of product risk per unit is positive. As long as the firm produces, (A.6) is satisfied. The denominator is positive and continuous. The (θ, p) space consists of an open set shown in the Fig. 3. The case where the firm's marginal cost of product risk per unit is negative proceeds in a similar way.

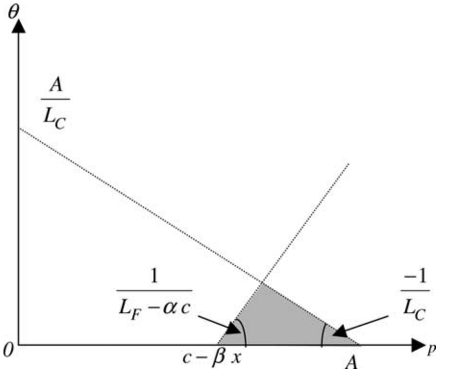

Fig. 3. Quality and price space.

Appendix B. Price distortion

The purpose of this appendix is to derive the relationship between the equilibrium prices and information structures.

With hidden information or hidden action, the firm does not charge the corresponding optimal price for the observable quality. The price when the consumer has knowledge of the product's quality is

$$p^{\mathrm{I}} = \frac{2\gamma(A + \theta(L_{\mathrm{F}} - \alpha c - L_{\mathrm{C}}) + c) - b\beta^2(A - \theta L_{\mathrm{C}})}{4\gamma - b\beta^2}. \tag{B.1}$$

Proposition B.1.

- *If the firm's marginal cost of product risk per unit is positive* $(L_{\mathrm{F}} - \alpha c > 0)$, *the price when the consumer has knowledge of product quality is not lower than the price with hidden information which is not lower than the price with hidden information and hidden action, that is,* $p^{\mathrm{I}} \geq p^{\mathrm{U}} \geq p^{0}$.
- *If the firm's marginal cost of product risk per unit is negative* $(L_{\mathrm{F}} - \alpha c < 0)$, *the price with hidden information is not lower than the price when the consumer has knowledge of product quality which is not lower than the price with hidden information and hidden action, that is,* $p^{\mathrm{U}} \geq p^{\mathrm{I}} \geq p^{0}$.

Proof. The difference between the price with hidden information and with hidden information and hidden action comes from the amount of R&D the firm undertakes. The amount of R&D undertaken when the amount is unobservable is larger than when it is observable, since

$$x^{\mathrm{U}} - x^{0} = \frac{-4b\beta\gamma L_{\mathrm{C}}(A - c - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}))(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}})}{\mathrm{DEN}^{\mathrm{U}}\{4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - b\beta^2(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})\}}, \tag{B.2}$$

where the denominator is positive by Assumptions 1 and 3, and the numerator is negative. The price with hidden information is always higher than the price with hidden information and hidden action, that is, $p^{\mathrm{U}} \geq p^{0}$.

The price when the consumer has knowledge of product quality is higher (lower) than the price with hidden information, when the firm's marginal cost of product risk per unit is positive (negative),

$$\begin{aligned} &L_{\mathrm{F}} - \alpha c > (<)\, 0 \Leftrightarrow 0 < (>)\, p^{\mathrm{I}} - p^{\mathrm{U}} \\ &\quad = \frac{\begin{array}{c}2\gamma L_{\mathrm{C}}(A - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - c)[(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) \\ \{4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - b\beta^2(L_{\mathrm{F}} - \alpha c)\} - 2b\beta^2 L_{\mathrm{C}}]\end{array}}{\mathrm{DEN}^{\mathrm{I}}\mathrm{IDEN}^{\mathrm{U}}}, \end{aligned} \tag{B.3}$$

where the denominator is positive from the second order condition, $(A - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - c)$ is assumed to be positive to ensure that demand is positive for $\theta < 1$, and $2b\beta^2 L_{\mathrm{C}}$ is assumed to be negligibly small. When $L_{\mathrm{F}} - \alpha c$ is positive, the ranking of the prices is $p^{\mathrm{I}} \geq p^{\mathrm{U}} \geq p^{0}$.

The price when the consumer knows the product quality is higher than the price with hidden information and hidden action,

$$p^{\mathrm{I}} - p^0 = \frac{8\gamma^2 L_{\mathrm{C}}(A - \theta(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - c)}{\mathrm{DEN}^{\mathrm{I}}\{4\gamma(L_{\mathrm{F}} - \alpha c + L_{\mathrm{C}}) - b\beta^2(L_{\mathrm{F}} - \alpha c + 2L_{\mathrm{C}})\}} \geq 0. \tag{B.4}$$

When $L_{\mathrm{F}} - \alpha c$ is negative, the ranking of the prices is $p^{\mathrm{U}} \geq p^{\mathrm{I}} \geq p^0$. □

With hidden information or hidden action, a price distortion occurs to signal that the quality of the firm's product is high. This distortion decreases the firm's profits compared to the profits when quality is observable.

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