# PRODUCT SAFETY: LIABILITY, R&D AND SIGNALING*

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December, 1992
Last Revision: January, 1994

* The financial support of NSF grants SES91-12914 and SES92-23087 is gratefully acknowledged.

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**ABSTRACT**

This paper develops a two-stage model of product design and safety signaling incorporating a parametric liability specification in a monopoly context. In the first stage, the firm engages in research and development in order to determine the safety of its product. We model the research and development process as sequential sampling from a fixed distribution of potential safety levels. Thus, R&D is a stochastic process, partially controlled by investment, which ultimately yields an equilibrium set of acceptable safety levels. Since the outcome of research and development trials is unobservable to consumers, in the second stage of the model the firm must choose its price with the understanding that consumers may attempt to draw inferences about the product's safety from the firm's pricing behavior. Given the price, consumers infer the level of safety and choose the amount of the product to acquire; injuries then lead to losses which are allocated by the particular liability system in place. We vary the liability system's allocation of losses and trace out the implications for the level of R&D investment and the relationship between price and safety.

We find that pricing and liability jointly distribute the value and losses associated with the product. When the liability system is firm-oriented, signaling distortions involve high prices to signal safety when the firm's liability is small compared with the cost reduction associated with lower safety, and low prices to signal safety when the liability exceeds the cost reduction. When the liability system is consumer-oriented, risky products require higher prices to compensate for large potential downstream liabilities of the firm. We also find that the average level of product safety under incomplete information is lower than would, on average, obtain under full information. The amount of R&D investment with regards to safety of the product is influenced by the firm's level of liability and the cost of producing the product. More precisely, when the firm's liability is less than the cost reduction, R&D activity may be used to lower product safety. When the firm's liability is greater than the cost reduction, R&D will be used to increase safety, but again, not on average to the level that would obtain under full information.

In this latter case, the possibility of less safe products creates an externality for all products in the equilibrium producible set: safer products must distort their prices (downward) even more than would occur otherwise, in order to signal safety. This suggests that, <u>ex ante</u>, a firm would like a minimum safety standard set high enough to preclude some (comparatively less safe) products that would have been producible in a noncooperative equilibrium.

**Product Safety: Liability, R&D and Signaling**

## 1. Introduction

Product quality frequently has multiple dimensions. Effectiveness (how well the product does its job), durability (how long it does its job) and safety (does the operation or use of the product risk injury[1]) are three attributes discussed in various portions of the literature. The incentive to ensure and/or signal effectiveness and durability typically relies on the existence of a reputation worth maintaining (e.g., to induce repeat sales), the employment of a warranty, or possibly both. The third attribute, however, typically involves liability law, with incidences of injury potentially leading to lawsuits and damage awards. For example, if a consumer's toaster doesn't toast or it burns out within the warranty period, then the consumer often can return the toaster and get a new one. If the toaster overheats and explodes, causing injury, action beyond the warranty is usually involved: a lawsuit is often entailed, involving lawyers, courts and bargaining over the level of damages and the liability of the manufacturer. Most manufacturers of products recognize this potential outcome, and some level of care is employed to balance the current production costs and potential downstream liabilities with the willingness of consumers to pay for the product at hand. This problem becomes especially complex when the level of safety of the product is not observable by the consumer prior to use. Of course, such problems are not limited to the world of toasters; drugs, lawnmowers, automobiles, homes and children's toys all readily come to mind.

This paper develops a two-stage model of product design and safety signaling incorporating a parametric liability specification in a monopoly context. In the first stage, the firm engages in research

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[1] We will use the word injury to cover bodily harm, adverse side-effects (such as from drugs) or other sources of unintended losses in utility or money terms.

and development in order to determine the safety of its product. Since the outcome of research and development trials is unobservable to consumers, in the second stage of the model the firm must choose its price with the understanding that consumers may attempt to draw inferences about the product's safety from the firm's pricing behavior. Product safety (or, more precisely, its converse, product risk) is represented by the probability of injury. Given the price, consumers infer the level of safety and choose the amount of the product to acquire; injuries then lead to losses which are allocated by the particular liability system in place. We vary the liability system's allocation of losses and trace out the implications for the level of R&D investment and the relationship between price and safety. We find that the equilibrium level of R&D activity and the price-safety path depend upon the relative costs to the firm of production and future potential liability, and to the consumer of immediate use and potential injury.

More precisely, first consider the second stage results under varying informational treatments and exogenously determined safety level. Under full information (i.e., when product safety is observable to consumers prior to use), the price-safety relationship depends entirely on which party is allocated more of the losses in the event of an injury. For instance, if the legal system leaves injured consumers largely uncompensated, then the full information price schedule involves higher prices for safer products; alternatively put, consumers must be offered lower prices if they are to assume a greater risk. If, however, consumers are largely compensated for damages due to injury, then the full information price schedule involves higher prices for riskier products; the expected compensation paid to injured consumers is reflected in higher marginal costs, and thus higher prices, for the firm.

When the firm is privately informed about its product's safety (i.e., when product safety is unobservable to consumers prior to use), the price-safety relationship is somewhat more complex. In particular, for some parameters for which the full information price schedule involves higher prices for safer products, the revealing equilibrium with private information involves lower prices for safer products; essentially, the firm with a safer product provides a credible "signal" of its safety by selling a large volume of the product (i.e., by increasing its exposure to future liability claims), which it accomplishes by offering the product at a low price.

Now let us consider the first stage, wherein the level of R&D investment is endogenously determined. We model the research and development process as sequential sampling from a fixed distribution of potential safety levels. Thus, R&D is a stochastic process, partially controlled by investment, which ultimately yields an equilibrium set of acceptable safety levels. Alternatively put, the type space for the signaling subgame is endogenously determined. We find that there are two relevant parameter regimes. If the firm's incremental savings in terms of expected liability from producing a marginally safer product exceeds the associated marginal production cost increase, then the firm's optimal policy is to set a reservation safety level and discontinue R&D and begin production when it develops a product which is at least as safe as that level. In this case, private information results in (on average) less R&D and the provision of products which are (on average) less safe than under full information. Moreover, we show that under these circumstances a firm's profits could be improved by safety regulation which takes the form of a minimum-safety standard.

On the other hand, if the firm's incremental savings in terms of expected liability from producing a marginally safer product are less than the associated marginal production cost increase, then the firm's optimal policy is to set a reservation safety level and discontinue R&D and begin production when it develops a product which is no safer than this level. A fortiori, private information results in the provision of products which are (on average) less safe than under full information.

There are many papers which examine the relationship between price and quality, far too many to survey thoroughly in a few pages. The interested reader is referred for a recent survey to Stiglitz (1987). We will be focusing on the following question: to what extent can price serve as a signal of quality (e.g., product safety) and what form does such signaling take? Work related specifically to this issue has been done by Milgrom and Roberts (1986), Lutz (1989), Bagwell and Riordan (1991) and Shieh (1993). All of these models assume that quality is exogenous and that there are two potential quality levels. Bagwell and Riordan describe a two-period model; in the second period, experience with the good has revealed its quality so that full information prevails. In the first period uninformed consumers can determine the good's quality only through purchase and consumption (i.e., it is an experience good). They assume that the marginal cost of production is higher for higher quality goods, and there are no other future implications of first-period pricing. In this case, high quality is signaled by a "high" price (one which exceeds the full information price for high quality) in the first period; in the second period the price falls to its full information level. This generates a pattern of "high and declining prices" for new products, which is characteristic of a number of products listed by Bagwell and Riordan. Milgrom and Roberts and Shieh employ the idea of repeat purchases to generate future implications for current pricing decisions. If the value of having a large initial customer base (which generates a large number of repeat purchases for high quality firms) dominates whatever marginal cost increases are associated with higher quality, then high quality will be associated with a "low" price (one which is lower than the corresponding full information price). In addition to examining the ability of price to signal quality, Milgrom and Roberts ask when advertising[2], a second potential signal, will be used; Lutz conducts a similar analysis when the second potential signal is the extent of warranty[3]. Shieh examines the impact of the need to signal quality through price on the firm's incentives to make unobservable investments in cost-reducing R&D.

There is also a voluminous literature on liability and incentives to take care. A classic paper by Diamond (1974) examines various liability rules (e.g., negligence, comparative negligence) and their impact on care-taking in the context of "single activity accidents" (i.e., representative agents engage in a single activity, during the course of which any two can be involved in an accident). In this model, care-taking by either party reduces the likelihood of an accident. More recently, P'ng (1987) examines the effect of the negligence standard on settlement rates and incentives to take care, while Polinsky and Rubinfeld (1988) examine the effect of settlement versus trial on incentives to take care, both employing models in which a potential injurer can invest in care-taking to avoid harming a potential

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[2] Kihlstrom and Riordan (1984) ask whether advertising alone can serve as a signal of quality; they find that, if repeat purchases are unaffected by current advertising (e.g., if all consumers learn about quality through the consumption of others), this is possible only if producing higher quality involves higher fixed, but not marginal, production costs. If repeat purchases are increased by current advertising (e.g., if only first period consumers learn about quality), then advertising can signal quality even if higher quality has somewhat higher marginal production costs. Matthews and Fertig (1989) describe a model in which an incumbent firm and a potential entrant use advertising to signal the entrant's quality level, and Yang (1991) develops a duopoly model in which both firms jointly signal their quality levels via advertising expenditures alone.

[3] Other papers which examine warranties as potential signals are Spence (1977), Grossman (1981), and Gal-Or (1989).

victim. In most cases, analyses of liability and incentives for care-taking either deal with non-market situations, or omit in-depth analysis of related market transactions. An exception is Simon (1981), in which competitive firms produce an experience good with the potential for injury, and invest in accident reduction subject to a negligence standard. Consumers are assumed to purchase one unit of the good in a competitive market; thus the price cannot serve as a signal of safety in this model. If injured, consumers must decide whether to file suit or not, based on their assessment regarding the likelihood that the product was negligently produced. Simon finds a stable mixed-strategy equilibrium in which negligent and non-negligent firms co-exist in the market.

In our model, the liability system provides an allocation of losses, but market transactions (where demand depends upon consumers' perceptions of safety) permit a market re-allocation of this liability-generated risk. Similarly, although the product's safety is unobservable prior to use, it may be revealed by the firm's pricing behavior. Our modeling of the market transaction distinguishes this work from the liability and incentives literature, while our concern with liability as a determinant of the relationship between price and safety distinguishes this work from the price-quality signaling literature.

We will maintain the assumption that the product is an experience good. We will assume that the firm first conducts R&D which results in a (randomly distributed) safety level;[4] it then chooses an

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[4] Thus, our approach to endogenous quality differs from the literature on "quality-guaranteeing prices," in which competing firms determine quality endogenously. Therein a price premium for higher quality products ensures that firms would rather maintain high quality than take advantage of consumers by providing low quality at the high price for one period and lose future sales from consumers they have "ripped off." Representative papers in this area include Allen (1984), Chan and Leland (1982), Cooper and Ross (1984,1985), Klein and Leffler (1981), Riordan (1986), Rogerson (1983,1987), Shapiro (1983) and Wolinsky (1983).

associated price. We will consider only a single potential signal: price. While focusing on price as the signal is primarily for simplicity, it is often difficult for consumers to observe the firm's total advertising expenditures (especially for one product among the many the firm produces) and to link them to safety (for example, prescription drugs are advertised to physicians, but sold to consumers), and compensation for potentially serious physical injuries or large losses goes beyond the standard warranties provided for effectiveness and durability. Finally, we assume that the product is one of a number the firm produces and that bankruptcy due to potential aggregate liability claims for this product is not possible.

Unlike the previous price-quality signaling literature, we will consider a continuum of possible safety levels. We will also assume that higher safety is associated with higher marginal production costs (due to, e.g., costlier inputs). We will not be concerned with repeat purchases or the pattern of prices over time. Rather, we will show how the extent of firm liability affects the equilibrium R&D investment and price-safety relationship.

In Section 2 we specify our basic model in more detail. In Section 3 we calculate the monopoly price-safety schedule which would obtain if consumers could observe safety prior to use. In Section 4 we consider monopoly pricing when consumers are unable to observe safety prior to use, but make inferences about safety from the firm's price. Section 5 examines how R&D decisions are made when safety is observable and unobservable. Section 6 summarizes our results and suggests some extensions.

## 2. Basic Model Set-Up

We assume that research and development activities result in a product which is effective, but results in an injury some of the time. Assume that R&D output is a draw from the distribution $\Phi(\theta)$ on [0,1], where $\theta$ represents the likelihood of an injury per unit used. After the firm observes the safety level $\theta$, it may elect to discontinue R&D and manufacture the product, it may continue to conduct R&D (at a cost of k), or it may decide to abandon the realized product and discontinue R&D. Thus not all realized values of $\theta$ will actually be produced. Let the interval [$\underline{\theta}$,], a non-empty subset of [0,1], represent the set of risk levels associated with products which will actually be offered for sale in equilibrium. For now, we treat $\underline{\theta}$ and  as exogenous; in Section 5 we describe how they are endogenously determined. From the firm's point of view, a realized value of $\theta$ is immutable, a by-product of the product design generated by the R&D activity. Any changes in $\theta$ must therefore come from doing more R&D (finding a new design, taking a new draw from the distribution $\Phi$).

Let L be the <u>total</u> losses generated by an injury due to the purchase and use of a unit of the firm's product. Thus, this includes lost time on the job by the consumer, legal fees of both parties, indirect costs the firm must bear to respond to a suit (such as lost use of managers needed for the case), as well as physical, mental and other damages suffered by the consumer. We will focus on a system involving strict liability, which means that the firm pays compensation without regard to issues of negligence: even firms with very safe products can be strictly liable. Thus, punitive damages (assessed for negligence or for social purposes of signaling other firms) do not exist in this model and are not in L. The <u>liability system</u> determines the amount of compensation (a transfer) from the firm to the consumer, and thus allocates L amongst the two parties.

Let $L_C \geq 0$ denote the uncompensated loss to the consumer if an injury occurs, and let $L_F \geq 0$ denote the corresponding loss to the firm. Thus, the consumer need not be "made whole;" for example, the outcome of the settlement and litigation process may only compensate the consumer for, say, physical damages, leaving pain and suffering, or legal fees, uncompensated. While the consumer need not prove negligence to obtain compensation, the firm may not be held liable for all losses that the consumer actually incurs. We also assume that firms self-insure, and thus $L \equiv L_F + L_C$.

We assume that a safer product is more costly to produce. Let the unit cost of production take the form $C(\theta) = c(1-\alpha\theta)$, where $c > 0$ and $\alpha \in [0,1]$. The firm thus has an "effective (or total) unit cost" of $c(1-\alpha\theta) + \theta L_F$; each unit produced costs $c(1-\alpha\theta)$ and generates a probability $\theta$ of a loss in the amount $L_F$.

In the sequel, we will maintain the following assumption, which ensures that under full information the marginal social gain from an increase in safety (L) exceeds the marginal social cost ($\alpha c$) of producing that increase.

Assumption 1. $L - \alpha c > 0$.

## 3. Pricing With Observable Safety

The consumer's demand function depends on the drug's "effective price," $p + \theta L_C$. Each unit costs p and generates a probability $\theta$ of a loss in the amount $L_C$. Let demand be given by $x(p) = a - b[p + \theta L_C]$. Thus the "effective maximum willingness to pay," the demand intercept, can be viewed as being $a/b - \theta L_C$. Profits to the firm can be written:

$$\pi(p,\theta) = [a - b(p + \theta L_C)][p - c(1-\alpha\theta) - \theta L_F].$$

Maximizing profit with respect to p under the assumption that consumers know $\theta$ yields the pricing formula:

$$p^I(\theta) = [a/b - \theta L_C + c(1-\alpha\theta) + \theta L_F]/2,$$

where the superscript "I" indicates that consumers are informed about product safety. The price $p^I(\theta)$ is the average of $a/b - \theta L_C$ and $c(1-\alpha\theta) + \theta L_F$. Notice that $dp^I(\theta)/d\theta = (L_F - \alpha c - L_C)/2$.

Essentially, $L_F - \alpha c$ is the "marginal cost of risk per unit sold" to the firm; a marginal increase in the risk as measured by $\theta$ increases the firm's potential legal judgments by the amount $L_F$ but reduces its unit production costs by the amount $\alpha c$. The expression $L_C$ is the corresponding "marginal cost of risk per unit purchased" to the consumer; a marginal increase in risk increases the consumer's expected loss by the amount $L_C$.

These two marginal costs allow us to characterize the orientation of the liability system as follows. If $L_F - \alpha c > L_C$ we call the system "consumer-oriented," since the allocation of losses is shifted toward the firm. Similarly, if $L_F - \alpha c < L_C$, we call the system "firm-oriented," since the allocation of losses favors the firm. A neutral system would be one wherein the two marginal costs were just equal.[5]

When the liability system is neutral, the firm charges the simple monopoly price $[(a/b)+c]/2$, independent of the value of $\theta$. Thus, a neutral system isolates the market transaction from any subsequent considerations of the extent of safety. When the system is consumer-oriented the price $p^I(\theta)$ is increasing in $\theta$: consumers are paying more in the market, part of which is a contribution to cover the (differential) liability costs of the firm. Finally, when the system is firm-oriented, $p^I(\theta)$ is decreasing in $\theta$: the firm is discounting the product in the market, essentially sharing some of the (differential) liability costs of the consumers. This is done to help temper the negative effect on demand of the absolute level of the consumer's potential loss.

Profits with observable safety are $\pi^I(\theta) = \pi(p^I(\theta),\theta) = (b/4)[a/b - c(1-\alpha\theta) - \theta L]^2$. Assume that $a/b - c(1-\alpha\theta) - \theta L > 0$ for all $\theta \in [0,1]$, so any possible risk type would yield positive profits if produced. Differentiating with respect to $\theta$ yields $d\pi^I/d\theta < 0$ if $L_C + L_F - \alpha c > 0$. That is, lower risk (safer) firms have higher profits so long as the combined marginal cost of risk is positive. Assumption 1 guarantees that this inequality holds; thus a firm producing a safer product enjoys higher profits when consumers can observe safety.

[5] While one might be tempted to consider the point where $L_F = L_C$ as neutral, this neglects the benefit that the firm received in lowered marginal production costs, namely $\alpha c$. Since any legal action would follow the production process, it is reasonable to expect a complete accounting of gains and losses, and that neither party should "benefit from ill-gotten gains."

4. Pricing With Unobservable Safety

Now suppose that the realized safety level $\theta$ is private information for the firm. This would be the case for new products with which there has been little experience. One might assume (as in Bagwell and Riordan) that after a preliminary period, experience with the product will reveal $\theta$; however, this preliminary period could be quite long for some products. During this period consumers may try to draw some inference about safety from the price at which the product is offered and/or the quantity distributed. We assume that the interval $[\underline{\theta},]$ is known to consumers, as is the distribution function $\Phi(\theta)$. Since $\underline{\theta}$ and will (in the next section) be determined endogenously as part of the equilibrium, it is reasonable to assume that consumers "know" them in the pricing subgame.

Let $\Theta(p)$ denote the consumer's "perceived safety" upon observing the price p; we continue to use $\theta$ to denote the true realized safety level. Now the firm's profits will depend on its true $\theta$, its price, and the consumer's perceptions or beliefs $\Theta(p)$.

$$\Pi(p,\theta;\Theta(p)) = [a - b(p + \Theta(p)L_C)][p - c(1-\alpha\theta) - \theta L_F]. \qquad (1)$$

We will be looking for a revealing equilibrium, in which each $\theta$ is associated with a different equilibrium price. Maximizing expression (1) with respect to p yields the first-order condition below, where p* denotes the equilibrium price.

$$-b[1 + \Theta'(p^*)L_C][p^* - c(1-\alpha\theta) - \theta L_F] + [a - b(p^* + \Theta(p^*)L_C)] = 0. \qquad (2)$$

In order for the equilibrium profits to be non-negative, it must be that both the equilibrium quantity and profit margin are positive. That is, it must be that $a - b(p^* + \Theta(p^*)L_C) > 0$ and $p^* - c(1-\alpha\theta) - \theta L_F > 0$. Using equation (2), these imply that $1 + \Theta'(p^*)L_C > 0$.

Equation (2) is an ordinary differential equation which characterizes the (unknown) equilibrium price-safety schedule $p^*(\theta)$. Although it is somewhat nasty, it turns out to be of a special, solvable form, and yields the following (implicit) solution: $p^*(\theta)$ satisfies

$$\{a/b - \theta L_C - p\}^{L-\alpha c}\{2p - c(1-\alpha\theta) - \theta L_F - [(a/b)(L_F - \alpha c) + cL_C]/(L - \alpha c)\}^{L_C} = K, \tag{3}$$

where K is a constant to be determined by imposing an appropriate boundary condition. The appropriate boundary condition is that, in a revealing equilibrium, the least safe product does not distort its price (no one wants to be mistaken for producing the least safe product, since this only depresses demand); that is, $p^*() = p^I()$. This yields the value:

$$K() \equiv \{[a/b - c - (L - \alpha c)]/2\}^{L-\alpha c+L_C}\{2L_C/(L - \alpha c)\}^{L_C}.$$

To gain some insight into the implied form of $p^*(\theta)$, notice that equation (3) describes a hyperbola in $(\theta,p)$ space. To see this, we define new coordinates $u \equiv a/b - \theta L_C - p$ and $v \equiv 2p - c - \theta(L_F - \alpha c) - [(a/b)(L_F - \alpha c) + cL_C]/(L - \alpha c)$. The origin in $(u,v)$ space corresponds to the coordinates $(\theta^o,p^o)$ in $(\theta,p)$ space, where $\theta^o \equiv (a/b - c)/(L - \alpha c) > 1$ and $p^o \equiv$

$[(a/b)(L_F - \alpha c) + cL_C]/(L - \alpha c)$. It is straightforward to show that $L_F - \alpha c > L_C$ implies that $p^o > p^I() > p^I(\underline{\theta})$, while $L_F - \alpha c < L_C$ implies that $p^o < p^I() < p^I(\underline{\theta})$. In the positive orthant of $(u,v)$ space, for each u there exists a unique v such that $u^{L-\alpha c}v^{L_C} = K()$. That is, the equation $u^{L-\alpha c}v^{L_C} = K()$ describes a hyperbola in (u,v) space. Solutions with $u < 0$ yield negative profits; if $u > 0$ but $v < 0$, then the solution involves imaginary roots. So it is the solution with both $u > 0$ and $v > 0$ which is of interest.

The rotation and shifting of the (u,v) space hyperbola into (θ,p) space gives a hyperbola with two p-values for each θ. Which of these provides the separating equilibrium we are seeking? Upon differentiating equation (3), we find that $dp^*/d\theta = L_C(p^*(\theta) - c - \theta(L_F - \alpha c))/2(p^I(\theta) - p^*(\theta))$. Since the numerator is always a finite positive number, $|dp^*/d\theta| = \infty$ at $\theta =$ (since $p^I() = p^*()$). For $\theta <$ , the lower branch involves $p^I(\theta) > p^*(\theta)$ with $p^*(\theta)$ increasing and convex; the upper branch involves $p^I(\theta) < p^*(\theta)$ with $p^*(\theta)$ decreasing and concave.

But only one branch is consistent with profit maximization. To determine which, note that the second-order condition for p* to provide a maximum is as follows.

$$d^2\Pi/dp^2 = -2b[1 + \Theta'(p^*)L_C] - b[p^* - c(1-\alpha\theta) - \theta L_F]\Theta''(p^*)L_C < 0.$$

Since equation (3) must hold for all θ along the equilibrium price schedule $p^*(\theta)$, total differentiation of (3) with respect to θ yields:

$$(d^2\Pi/dp^2)(dp^*/d\theta) + b[1 + \Theta'(p^*)L_C](L_F - \alpha c) = 0. \quad (4)$$

We have already shown that $1 + \Theta'(p^*)L_C > 0$, so sgn $dp^*/d\theta$ = sgn $\{L_F - \alpha c\}$. That is, if the firm's marginal cost of risk per unit is positive, then $p^*(\theta)$ will be increasing, while if the firm's marginal cost of risk per unit is negative, then $p^*(\theta)$ will be decreasing. Interpreting high safety (low θ) as high quality, this says that high quality will be signaled by a low price whenever $L_F - \alpha c > 0$. Here, lower quality firms have higher unit costs (due to the inclusion of liability costs) and would mimic higher prices if consumers believed high quality was associated with high price. On the other hand, if $L_F - \alpha c$

< 0, then higher quality is associated with higher unit costs and can thus be signaled through charging a higher price. If $L_F - \alpha c = 0$, then all safety types have the same unit costs and no revealing equilibrium can exist.

The natural out-of-equilibrium beliefs which support this equilibrium associate an out-of-equilibrium message with the sender of the closest equilibrium message. That is, when $L_F - \alpha c > 0$, an out-of-equilibrium price p > p*() generates the belief Θ*(p) = and an out-of-equilibrium $p < p^*(\underline{\theta})$ generates the belief $\Theta^*(p) = \underline{\theta}$. Conversely, when $L_F - \alpha c < 0$, then

an out-of-equilibrium price $p > p^*(\underline{\theta})$ generates the belief $\Theta^*(p) = \underline{\theta}$ and an out-of-equilibrium p < p*() generates the belief Θ*(p) = . In the Appendix we show that these beliefs support the equilibrium.

<u>Proposition 1</u>. (a) If $L_F - \alpha c < 0$, then $p^*(\theta) > p^I(\theta)$ for θ < , and both price schedules are decreasing functions of θ.

(b) If $0 < L_F - \alpha c < L_C$, then $p^*(\theta) < p^I(\theta)$ for θ < ; the revealing price schedule is an increasing function of θ, while the price schedule with informed consumers is a decreasing function of θ.

(c) If $L_F - \alpha c > L_C$, then $p^*(\theta) < p^I(\theta)$ for θ < , and both price schedules are increasing functions of θ.

Evaluating the profit function at $p^*(\theta)$ yields $\Pi^*(\theta) \equiv \Pi(p^*(\theta),\theta;\Theta^*(p^*(\theta))) = [a - b(p^*(\theta) + \Theta^*(p^*(\theta))L_C)][p^*(\theta) - c(1-\alpha\theta) - \theta L_F]$. By the envelope theorem, $d\Pi^*/d\theta = -[a - b(p^*(\theta) + \Theta^*(p^*(\theta))L_C)](L_F - \alpha c)$. Since the term in brackets is positive, sgn $d\Pi^*/d\theta$ = - sgn $\{L_F - \alpha c\}$. That is, if higher-risk products entail higher unit costs (due to, e.g., relatively large expected liability losses), then they have lower equilibrium profits. On the other hand, if higher-risk products entail lower unit costs (due to, e.g., relatively large marginal production cost savings), then they have higher profits.[6] Recall that with full information, Assumption 1 is sufficient to imply that higher risk firms always have lower profits.

Proposition 2.(a) The revealing equilibrium profit function is an increasing function of $\theta$ (higher-risk products have higher equilibrium profits) if $L_F - \alpha c < 0$.

(b) The revealing equilibrium profit function is a decreasing function of $\theta$ (higher-risk products have lower equilibrium profits) if $L_F - \alpha c > 0$.

For all values of $\theta <$ , firms are worse off under asymmetric information; this follows directly from the fact that their risk types are revealed, but they are not charging the corresponding optimal price for observable safety. The highest risk type does not distort either its price or its profits, and thus receives the same profits with unobservable safety as with observable safety.

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[6] A necessary condition for a revealing equilibrium is that products with higher total unit costs $c + (L_F - \alpha c)\theta$ have lower equilibrium profits. To see why, assume otherwise, i.e., that they have the higher profits. Then products with lower total unit costs could mimic the pricing strategy of those with the higher total unit costs, achieving the same revenues. However, this would mean that the products with lower total unit costs would have higher profits yet, contradicting the assumption. Essentially, the lower total unit cost products must receive higher profits to prevent mimicry.

Figure 1 illustrates the relationships expressed in Propositions 1 and 2. The line at the bottom of the figure represents possible values of $L_F$ - $\alpha$c. Recall that the liability system is neutral when this value is precisely $L_C$, i.e., when the two marginal costs of risk per unit are equal. Thus, panels (a) and (b) reflect price-safety paths, and the direction in which profits increase along these paths, when the liability system is firm-oriented. Panel (c), by contrast, reflects a liability system that is consumer-oriented. Note that in all cases, the linear path is the full information pricing path, while the curved path is the equilibrium pricing path under incomplete information.

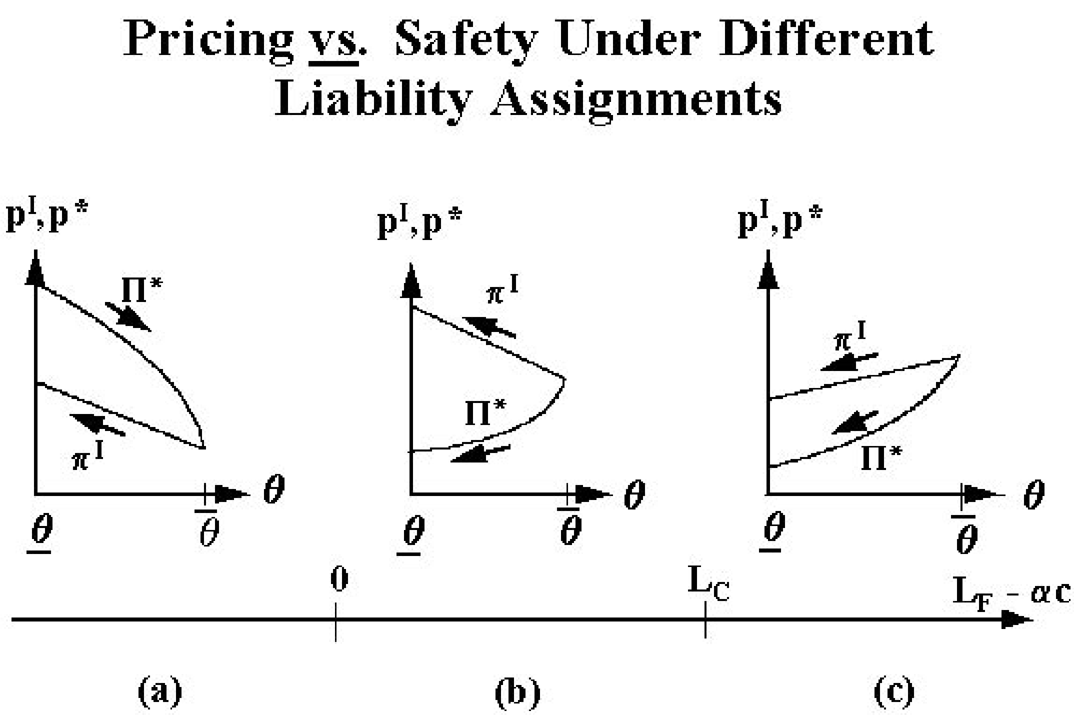


**Figure 1**

Case (a) (in the Figure and in the Propositions) arises when $L_F$ - $\alpha$c < 0; that is, when the marginal cost of producing a safer product is high relative to the firm's liability. Because the firm's liability is relatively low, the production cost reduction associated with lower-safety products means that firms that would produce such products would want to produce them in volume and therefore would want to set a low price. If safety is observable then firms with safer products make higher profits than those with less safe products because demand increases faster than cost does in response to safety; this is why the price-safety path under full information falls as $\theta$ rises. Thus, $\pi^I$ rises to the left along the $p^I(\theta)$ path shown in the diagram. If safety is unobservable, then firms with low safety (high $\theta$) would like to claim to be safer, but enjoy the cost benefits of low safety. This means that firms with low values of $\theta$ (i.e., safe products) must set even higher prices, so as to signal that they are not a low-safety (and therefore low-cost) firm. Thus, they price above the full information price. Finally, $\Pi^*$ is increasing in $\theta$ because firms with higher total unit costs have, in equilibrium, lower profits. In the case at hand, firms with safer products have higher unit production costs, and thus higher total unit costs.

Case (b) arises when $0 < L_F - \alpha c < L_C$; that is, the marginal cost of producing a safer product is low relative to the firm's liability. The liability system is still "firm oriented" since $L_F - \alpha c < L_C$. Note that firms now signal safe products by cutting price relative to $p^I$. This strategy makes claims of safe products credible since low prices yield high volumes, which means considerable exposure to the risk of a claim. Given the liability system, this exposure would be unprofitable for less safe products. Note that, once again, firms with higher total unit costs have lower equilibrium profits. This is why $\Pi^*$ is declining in $\theta$, since total unit costs involve both production and liability costs, and liability costs now outweigh the production cost reduction associated with lower safety.

Finally, case (c) above arises when $L_F - \alpha c > L_C$; that is, when the liability system is consumer-oriented. Note that, once again, the incomplete information case involves a firm with a high-safety product taking on exposure risk to signal that its $\theta$ is low. Note also that both p* and $p^I$ are increasing in $\theta$, reflecting the notion that the firm is shifting the liability costs towards the consumer through the market. This is consistent with the sometimes-heard notion that "we all pay for high awards" in liability cases.

5. Endogenous Determination of $\theta$ and

Recall that when consumers are informed about $\theta$, a firm with a higher-risk product makes lower profits. Although the entire range of products are profitable to produce, the firm may choose to engage in further R&D rather than producing a product with a given realized $\theta$. In particular, there may exist a reservation $\theta \in [0,1]$, denoted $\theta^I$, such that the firm continues to conduct R&D trials until it observes a $\theta$-value at or below the relevant reservation safety level. Thus the range of products which might be produced is given by $[0,\theta^I]$.

Suppose that it pays to conduct at least one R&D trial; that is, $\int \pi^I(t)d\Phi(t) > k$. If $\theta$ is the safest realized product to date, the firm can choose to discontinue R&D and go into production, yielding profit of $\pi^I(\theta)$, or to conduct another R&D trial at a cost of k. The firm retains the ability to produce the safest realized product to date. Thus the value of one more R&D trial is:

$$g(\theta) \equiv -k + \int_0^{\theta} [\pi^I(t) - \pi^I(\theta)]d\Phi(t). \qquad (5)$$

Notice that $g(0) < 0$ and $g(\theta)$ is an increasing function. Thus, if we further assume that $g(1) > 0$, then $\theta^I$ is the unique solution in (0,1) to $g(\theta) = 0$.

When safety is unobservable, consumers must form conjectures about which product types might be offered. Let $\underline{\theta}$ and  denote, respectively, the lowest-risk and highest-risk product types conjectured by consumers to be offered by the firm. The equilibrium price schedule, beliefs and profit function depend on the value  through the boundary condition. Thus let $p^*(\theta;)$, $\Theta^*(p;)$ and $\Pi^*(\theta;)$ denote these parametrized functions. Notice that, because the boundary condition only depends on , none of these functions depends on $\underline{\theta}$.

When $L_F - \alpha c > 0$ and safety is unobservable, then equilibrium profits are a decreasing function of $\theta$. Thus the range of products which might be produced in equilibrium is of the same form as when safety is observable: [0,*], where * denotes the equilibrium reservation safety level when safety is unobservable. We will first provide a necessary condition for defining * and then verify that firms will sample until they get a product with $\theta \leq$ * if that behavior is what consumers expect.

If the firm's safest realized product to date has risk $\theta \leq$ , and  is the (conjectured) riskiest product which will be produced in equilibrium, then the firm can discontinue R&D and go into production, earning profits of $\Pi^*(\theta;)$, or conduct another round of R&D, which may yield a safer product. In this case the gain, denoted $G(\theta;)$, from conducting one more R&D trial is:

$$-k + \int_0^{\theta} [\Pi^*(t;) - \Pi^*(\theta;)]d\Phi(t).$$

This gain is -k when evaluated at $\theta = 0$, and is an increasing function of $\theta$. Since profits are lower under asymmetric information, it may not pay to do R&D, but a sufficient condition to conduct at least one trial is that $\int \Pi^*(t;1)d\Phi(t) > k$. If an interior Nash equilibrium reservation value * exists, it must

(1) equate the gain from conducting one more R&D trial to zero and (2) be the highest risk product actually produced (that is, the consumers' conjectures will be correct). Thus the reservation value * is given by G(*;*) = 0, that is:

$$k = \int_0^{*} [\Pi^*(t;*) - \Pi^*(*;*)]d\Phi(t). \quad (6)$$

Since $\Pi^*(;) \equiv \pi^I()$ (the highest risk producer obtains the same profits as if the consumer were exogenously informed), and $\Pi^*(\theta;) < \pi^I(\theta)$ for all $\theta <$ , it follows that $G(\theta^I;\theta^I) < g(\theta^I) = 0$. Since G(;) is continuous in , a sufficient condition for the existence[7] of a Nash equilibrium reservation value $* \in (\theta^I,1)$ is $G(1,1) > 0$.

We have established that there exists * such that all $\theta \leq *$ will discontinue R&D and produce, pricing according to $p^*(\theta;*)$. In the Appendix we verify, using the consumer beliefs from Section 4, that firms drawing $\theta > *$ would prefer to continue R&D rather than producing a product of type $\theta$.

Proposition 3. When $L_F - \alpha c > 0$, the reservation safety level with unobservable safety (*) is higher than the reservation safety level with observable safety ($\theta^I$). The firm will conduct (on average) less R&D and produce (on average) less safe products when safety is unobservable.

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[7] Actually, there may be multiple solutions to equation (6), but all exceed $\theta^I$. To see this, note that $g(*) > G(*;*) = 0$. Since $g(\theta)$ is monotonically increasing, and $g(\theta^I) = 0$, it follows that $\theta^I < *$.

When $L_F - \alpha c < 0$, then less safe products make higher equilibrium profits. In this case, the firm might conduct more R&D because its lab has generated a product which is too safe and hence too expensive, given the need to signal safety, the low liability and the higher variable production cost.[8] For this parameter configuration, the reservation value is a lower bound on safety, so that the range of products which might be produced in equilibrium is of the form $[\underline{\theta}^*,1]$, while the range of products which might be produced with observable safety is still $[0,\theta^I]$. The expression $\underline{\theta}^*$ is thus determined by the equation:

$$k = \int_{\underline{\theta}^*}^{1} [\Pi^*(t;1) - \Pi^*(\underline{\theta}^*;1)]d\Phi(t). \qquad (7)$$

Once again, the firm will produce (on average) less safe products when safety is unobservable. However, it may now engage in more R&D as the firm rejects a product type that would have been acceptable were its safety level observable.

**Firm Demand for Safety Regulation**

When $L_F - \alpha c > 0$, equilibrium with unobservable safety involved, on average, less R&D activity and always generated a reservation safety value in excess of the full information safety value, thus suggesting a potential social benefit from minimum safety regulation. In this subsection we show that the firm has a private incentive to encourage such regulation.

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[8] An example might be a very costly, very safe drug with only mild side effects, which is made from a rare plant. The firm may then pursue development of a significantly cheaper but somewhat less safe synthetic alternative.

Recall that, for arbitrary , $p^*(\theta;)$ is defined by the following equation:

$$\{a/b - \theta L_C - p^*\}^{L-\alpha c}\{2p^* - c(1-\alpha\theta) - \theta L_F - [(a/b)(L_F - \alpha c) + cL_C]/(L - \alpha c)\}^{L_C} = K().$$

Differentiation and simplification implies that sgn $\{\partial p^*(\theta;)/\partial\}$ = sgn $\{(L - \alpha c)/(p^*(\theta;) - p^I(\theta))\}$. The numerator is positive by Assumption 1 and $p^*(\theta;) < p^I(\theta)$ when $L_F - \alpha c > 0$. Thus $\partial p^*(\theta;)/\partial < 0$. Moreover, since $p^*(\theta;)$ is already "too low," it follows that $\partial \Pi^*(\theta;)/\partial < 0$ as well. That is, a higher "highest" risk type  imposes a negative externality on all safer products, which must all lower their prices even further to distinguish themselves. This suggests that a firm might, before conducting its R&D, advocate a rule or law or bureaucratic restriction which mandates a highest allowable risk  < *. The firm would thus trade off higher expected profits on product types with $\theta \leq$  for being prevented from selling product types with $\theta \in$ (,*]. More formally, suppose that the firm could commit <u>ex ante</u> to continuing R&D until it discovered a product with risk no greater than . Then expected profits would be:

$$-k/\Phi() + \int_0 \Pi^*(t;)d\Phi(t)/\Phi(), \tag{8}$$

where the term $k/\Phi()$ reflects the cost per trial times the expected number of trials required to obtain a $\theta \in [0,]$ and the expression $\Phi()$ appears in the integral to reflect the conditional distribution of $\theta$, given that $\theta \in [0,]$. Differentiating expression (8) with respect to  and collecting terms yields the following first-order condition:

$$[k - \int_0 (\Pi^*(t;) - \Pi^*(;))d\Phi(t)]d\Phi()/(\Phi())^2 + \int_0 (\partial\Pi^*(t;)/\partial)d\Phi(t)/\Phi() = 0. \tag{9}$$

Notice that the term in brackets is zero at  = *.  Thus equation (9), when evaluated at *, is negative since $\partial\Pi^*(\theta;)/\partial < 0$.  Assuming concavity of profits in , it follows that * > .

> Proposition 4.  When $L_F - \alpha c > 0$, the firm would (ex ante) prefer to be constrained to a lower reservation safety level  than to have * arise noncooperatively; this constraint would induce the firm to conduct (on average) more R&D and to produce (on average) safer products.

## 6.  Conclusions and Potential Extensions

In this paper we have provided a model wherein a firm is producing a product with imperfect and unobservable safety, the consequence of which may be injury to a consumer and liability-based losses for the firm.  We find that pricing and liability jointly distribute the value and losses associated with the product.  When the liability system is firm-oriented, signaling distortions involve high prices to signal safety when the firm's liability is small compared with the cost reduction associated with lower safety, and low prices to signal safety when the liability exceeds the cost reduction.  When the liability system is consumer-oriented, risky products require higher prices to compensate for large potential downstream liabilities of the firm.  Alternatively put, firms whose total unit costs are mostly influenced by production costs signal safety via high prices, while firms whose total unit costs are mostly influenced by liability losses signal safety through high volumes.

We also find that the average level of product safety under incomplete information is lower than would, on average, obtain under full information.  The amount of R&D investment with regards to safety of the product is influenced by the firm's level of liability and the cost of producing the product. More precisely, when the firm's liability is less than the cost reduction, R&D activity may be used to lower product safety. When the firm's liability is greater than the cost reduction, R&D will be used to increase safety, but again, not on average to the level that would obtain under full information.

In this latter case, the possibility of less safe products creates an externality for all products in the equilibrium producible set: safer products must distort their prices (downward) even more than would occur otherwise, in order to signal safety. This suggests that, ex ante, a firm would like a minimum safety standard set high enough to preclude some (comparatively less safe) products that would have been producible in a noncooperative equilibrium.

We have treated the case of a monopoly in which safety could only be revealed through pricing. Interesting extensions would involve multiple firms and access to independent testing options, which could provide credible verification of safety claims. Moreover, strategic use of this option by one or more firms might generate more or less coarseness of the information that consumers have about all products. For example, if firms had access to independent testing sources (e.g., Underwriters Laboratories, "tested at a major University," etc.) then competing firms might not limit themselves to having their own product's safety verified; they might engage in strategic testing of a competitor's products. Pricing then might involve less distortion than without such an agency. This might, in turn, lead to greater R&D investment.

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Appendix

**Discussion of Beliefs for the Pricing Subgame**

To see that the beliefs proposed for this subgame support the equilibrium, we must verify that no type $\theta \in [\underline{\theta},]$ would prefer an out-of-equilibrium price. When $L_F - \alpha c > 0$, all $p > p^*()$ yield profits of $\Pi(p,\theta;)$. Since $p^*()$ maximizes $\Pi(p,;)$ (the type does not distort its equilibrium price from its full-information price), $\partial\Pi(p,;)/\partial p\,|_{p^*()} = 0$. Thus $\partial\Pi(p,\theta;)/\partial p\,|_{p^*()} < 0$ for all $\theta <$ ; that is, the price $p^*()$ dominates any $p > p^*()$ for all $\theta \in [\underline{\theta},]$. All $p < p^*(\underline{\theta})$ yield profits of $\Pi(p,\theta;\underline{\theta})$. The price $p^*(\underline{\theta})$ maximizes $\Pi(p,\underline{\theta};\Theta^*(p))$, implying the first-order condition (2): $d\Pi(p,\underline{\theta};\Theta^*(p))/dp\,|_{p^*(\underline{\theta})} = 0$. Thus for $\theta > \underline{\theta}$, $d\Pi(p,\theta;\Theta^*(p))/dp\,|_{p^*(\underline{\theta})} > 0$; <u>a fortiori</u> $\partial\Pi(p,\theta;\underline{\theta})/\partial p\,|_{p^*(\underline{\theta})} > 0$ for all $\theta \in [\underline{\theta},]$, so $p^*(\underline{\theta})$ dominates any $p < p^*(\underline{\theta})$. The case wherein $L_F - \alpha c < 0$ can be dealt with in a similar manner.

<u>Claim</u>: Under the beliefs specified in Section 4, a firm drawing $\theta > *$ prefers to continue R&D rather than produce a product of type $\theta$.

<u>Proof</u>: If $\theta > *$ <u>were</u> to produce, what would be its optimal price? Consumers expect prices in the interval $[p^*(0;*), p^*(*;*)]$; any other price will trigger out-of-equilibrium beliefs. By previous arguments, any $p < p^*(0;*)$ is dominated by $p^*(0;*)$. The best price within the interval $[p^*(0;*), p^*(*;*)]$ is $p^*(*;*)$ since $d\Pi(p,\theta;\Theta^*(p;*))/dp\,|_{p^*(*;*)} > 0$ for $\theta > *$. Any $p > p^*(*;*)$ yields profit of $\Pi(p,\theta;*)$. Since $\partial\Pi(p,\theta;*)/\partial p\,|_{p^*(*;*)} > 0$ as well, the optimal price for $\theta$ to charge (were it to produce) is $(\theta;$

*) such that $\partial\Pi(,\theta;*)/\partial p = 0$; that is, $(\theta;*) = (a/b - *L_C + c(1-\alpha\theta) + \theta L_F)/2 > p*(*;*)$. The resulting profits are $(\theta;*) = \Pi((\theta;*),\theta;*)$, and $\partial(\theta;*)/\partial\theta < 0$.

Thus if the firm drawing a product with safety $\theta > *$ were to produce, it would charge the out-of-equilibrium price $(\theta;*)$ and allow itself to be taken as a product with safety *. Despite this advantageous (though mistaken) inference on the part of consumers, the θ-type would enjoy lower profits than the *-type: $(\theta;*) < \Pi*(*;*)$. This follows because, for all $\theta > *$ and all p, $\Pi(p,\theta;*) < \Pi(p,*;*) \leq \Pi*(*;*)$, where the latter inequality follows from the fact that $p*(*;*)$ maximizes $\Pi(p,*;*)$. Now consider the expected gain from one more R&D trial for a firm with current product type $\theta > *$:

$$G(\theta;*) = - k + \int_{0}^{*} [\Pi*(t;*) - (\theta;*)]d\Phi(t) + \int_{*}^{\theta} [(t;*) - (\theta;*)]d\Phi(t)$$

$$> G(*;*) = 0.$$

Thus the firm with product type $\theta > *$ prefers to continue R&D.