Product safety and harm mitigation incentives when mitigation lowers consumption benefits

Florian Baumann* Tim Friehe†

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Abstract

To reduce the expected harm its product causes to consumers, a firm can invest in a product's safety before sale or mitigate harm after sale in the event product risks materialize. After-sale harm mitigation interferes with consumers' product use and reduces consumption benefits. We describe a firm's incentives for safety investments and harm mitigation as a function of the level of the firm's liability. Whereas post-sale mitigation incentives are scaled up by liability, pre-sale product safety is a u-shaped function of liability, making the two harm reduction instruments substitutes at low levels of liability and complements at high levels. To induce efficient harm mitigation, liability must be less than full. Further reducing the level of liability improves product safety at the cost of the firm's profits.

Keywords: Product liability; product safety; harm mitigation

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*University of Bonn, Center for Advanced Studies in Law and Economics, Adenauerallee 24-42, 53113 Bonn, Germany. E-mail: fbaumann@uni-bonn.de.

†University of Marburg, Public Economics Group, Am Plan 2, 35037 Marburg, Germany. CESifo, Munich, Germany. EconomiX, Paris, France. E-mail: tim.friehe@uni-marburg.de.

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1 Introduction

1.1 Motivation and main results

After selling its product, a firm may learn that its product can cause harm to consumers. The firm can then choose to mitigate expected harm. Harm mitigation may be accomplished, for instance, in a physical product recall and repair. Many modern products also grant manufacturers remote access and thus may allow for harm mitigation through non-physical update of a product's software components.[1] In any case, harm mitigation is costly for the firm, possibly involving fixed costs for developing mitigation measures and variable costs in their application to individual product units. Product liability may be necessary to motivate the firm to incur these costs.

However, the after-sale mitigation of harm may also impose costs on consumers. Such costs may materialize from the temporary loss of consumers' use associated with repair time or corrective measures. For example, car owners may have to leave their vehicle at the repair shop, a laptop repair may require the prolonged attention of a local dealer, or a refrigerator may require shipment to the manufacturer for an exchange of defective parts.[2] Likewise, in the case of harm mitigation via software updates, it is a well-known drawback that such updates might interfere with product usage.[3] This repercussion of harm mitigation will bear more heavily on consumers with a high valuation for the product, implying that consumers with a higher

[1]For example, in 2014, NestLab updated the software for all of its WiFi connected smoke detectors when it was discovered that consumers could inadvertently deactivate them (OECD 2017, p. 11). The general consequences of this trend towards remote accessibility for consumer safety and other related aspects are widely discussed (see, for example, OECD 2017).

[2]See, for example, the recall announcement for a refrigerator on `haierappliances.com/recalls/haier-top-mount-refrigerator-recall` (last accessed February 28, 2019).

[3]A very direct consequence stems from temporarily restricted access to the product's capabilities. In addition to restricted access, consumption benefits may suffer long-term consequences from harm mitigation. Consider, for instance, operating systems for computers. Updates to address security vulnerabilities may be implemented remotely, but during this process conflicting software programs may be deleted or specific functions such as a web-camera or LAN port may be disabled. Along similar lines, the software updates necessary to address the design flaws in Intel's processor chips publicized in the beginning of 2018 are expected to seriously harm processor speed. Also, the extensive required software updates following Volkswagen's now infamous emissions scandal have reduced the emissions-specific expected harm, but at a likely detriment to fuel efficiency and performance.

product valuation experience greater losses in consumption benefits in the event of disruptive harm mitigation.

When firms can access the product remotely after sale, they can use harm mitigation (and thereby impose losses in consumption benefits) without soliciting consumers' consent at each instance. Currently, such remote access is possible for many products as they are connected to the internet (*"internet of things"*; see, e.g., Gubbi et al. 2013) or are otherwise electronically accessible. Using remote access, firms can either directly alter product characteristics using updates for the product's software components or can strongly incentivize the consumer to return the product, for example, by disabling essential product features. A case-in-point is the fire hazard posed by Samsung's Galaxy Note 7; the firm used a software update to disable battery charging and thereby "forced" consumers to hand in their product for repair.[4]

Our article examines a firm's incentives for *post-sale* harm mitigation and *pre-sale* product safety investments when the firm can use a post-sale remedy without having to ask for the consent of consumers who lose consumption benefits from the firm's harm mitigation. In contrast to the previous literature, we emphasize the important role played by consumption benefits lost due to harm mitigation. In our framework, we consider a monopolist who can increase the observable product safety level, thereby raising the probability that the firm's product will not cause any harm to consumers. If, despite this investment, the product turns out to be risky, the firm can employ a post-sale remedy. Both pre-sale safety investments and post-sale remedies are costly for the firm. The latter reduces expected harm but also lowers consumers' consumption benefits and is central to our incentive analysis.

Without product liability in place, the firm has no incentive to mitigate harm after sale. This lowers consumer willingness to pay for the product but the firm lacks the ability to commit to use the post-sale remedy more often. Making the firm fully liable for consumer harm induces harm mitigation that is excessive in terms of ex-ante profits because, when the firm decides on harm mitigation, it fails to internalize the marginal consumer's loss in consumption benefits. This means that with full liability, the subgame-perfect harm mitigation choice deviates from the harm mitigation choice maximizing ex-ante profits. However, a specific level of liability between no liability and full liability exists that incentivizes the firm to use the post-sale remedy

[4]See theguardian.com/technology/2016/dec/09/galaxy-note-7-samsung-software-update (last accessed March 25, 2019).

in a way that maximizes its ex-ante profits. In contrast, pre-sale product safety investments are always maximizing ex-ante profits (i.e., independent of the level of liability). This results because the product safety level is observable and established before the sale of the product, implying that the firm correctly anticipates that higher product safety investments increase the marginal consumer's willingness to pay.

We find that higher levels of liability always induce stronger incentives for harm mitigation. In contrast, higher liability can either encourage or discourage additional product safety investments. This holds because, for a given level of output, the minimal product safety level is reached at the partial level of liability aligning the firm's subgame-perfect harm mitigation choice with the one that maximizes ex-ante profits. In other words, product safety is a u-shaped function of liability. As a result, depending on the level of liability, the two harm-prevention instruments may be substitutes or complements. Specifically, when higher liability improves the alignment of the firm's subgame-perfect harm mitigation choice with the one that maximizes ex-ante profits, the materialization of product risks gets less costly for the firm such that product safety incentives are reduced. To the contrary, when higher liability means that the subgame-perfect harm mitigation choice diverges to a greater extent from the harm mitigation choice maximizing ex-ante profits, an inherently risky product poses higher costs for the firm, thus rationalizing higher product safety investments. Interestingly, any disparity between the subgame-perfect harm mitigation choice and the harm mitigation choice maximizing ex-ante profits can be influenced by the firm's strategic adjustment of output when mitigation costs include fixed costs.

Product liability can be used to bring about a better alignment of the firm's choices with the social optimum regarding both product safety investments and harm mitigation. There exists a level of liability between no liability and full liability that induces socially optimal harm mitigation incentives. This level of liability is smaller than the partial liability preferred by the firm (i.e., the level of liability that aligns the firm's subgame-perfect harm mitigation choice with the one maximizing the firm's ex-ante profits). This holds because the social planner focuses on the *average* consumer's consumption benefits lost due to mitigation whereas the firm considers the *marginal* consumer's lost consumption benefits (which are lower). Interestingly, starting from the level of liability that induces socially optimal harm mitigation, a further decrease in the firm's liability increases welfare. This results from the fact that, when choosing the level of liability, the social planner affects not only the firm's harm mitigation choice but also its product safety investments. The firm's focus on the marginal consumer implies that product safety falls short of the socially optimal level (as the social planner again considers the *average* consumer's loss of consumption benefits with any harm mitigation). Starting at the level that induces socially optimal harm mitigation (which is lower than the liability level maximizing the firm's ex-ante profits), the product safety investment can be raised by a decrease in the firm's level of liability. Consequently, this socially optimal level of liability is lower than the level of liability the firm desires as a commitment device to align the subgame-perfect harm mitigation choice with the harm mitigation choice maximizing ex-ante profits.

In addition to our main analysis, we briefly discuss several extensions. Central to our findings is that consumers lose consumption benefits when there is harm mitigation and that the firm fails to incorporate this repercussion in its post-sale remedy choice. In our first extension, we thus consider a setting in which the firm must pay a uniform transfer to consumers to (imperfectly) compensate for the lost consumption benefits. Next, we investigate the scenario in which the firm can differentiate products by varying the harm mitigation thresholds. This allows consumers with a high consumption valuation (i.e., consumers with high lost consumption benefits due to harm mitigation) to opt for a lower probability of harm mitigation. We also consider that consumers may contract with the firm after sale about possible harm mitigation in exchange for a transfer. Finally, we explain the potential of reputation concerns in terms of incentivizing the firm to choose ex-ante profit-maximizing harm mitigation. We find that aligning the firm's behavior with socially optimal choices is difficult even when additional instruments are available. However, as will be discussed, there are circumstances in which the firm's reputation concerns enable it to attain maximum ex-ante profits.

1.2 Related literature

Our analysis is related to the literature on product liability and contributions concerning product recalls. The extensive literature on product liability has been surveyed elsewhere, notably in Daughety and Reinganum (2013). An important result of the early literature deals with the potential irrelevance of product liability for market outcomes. When homogeneous consumers are perfectly informed about the product risk associated with the consumption of a unit of a firm's product, shifting losses to the firm is inconsequential for the levels of safety and output.

Firms will provide efficient product safety even without liability because consumers' willingness to pay increases with safety. This mechanism does not function perfectly for post-sale harm mitigation in our setup because consumers' willingness to pay can only depend on their expectation about future harm mitigation.[5]

Our analysis of harm mitigation is related to the literature on product recalls. Chen and Hua (2012) consider a setup comprised of both an ex-ante care measure and an ex-post instrument to address expected harm. In view of the relevance of Chen and Hua (2012), in Section 4 we provide a detailed discussion of their paper against the backdrop of our main analysis. In contrast to our ex-post remedy that may be imposed on consumers without their consent, Spier (2011) considers a monopolist's incentives for the buyback of defective products, finding that only a specific negligence rule can ensure the social welfare benchmark is met. Along similar lines, Hua (2011) analyzes the scenario in which consumers must be incentivized to visit a service facility in order to have product defects remedied. Both Spier (2011) and Hua (2011) primarily focus on incentives to motivate ex-post remedies, whereas the present paper is concerned with the availability of both ex-ante prevention and ex-post mitigation, where harm may be mitigated without having to obtain consumers' explicit consent. However, in our extensions, we also discuss how to incentivize consumers' agreeing to the mitigation of harm.[6]

Since altering a product's software is one way of mitigating harm, our paper may also be related to the literature on software defects and post-sale updates. One major concern in this literature has been the timely disclosure of software vulnerabilities (see, e.g., Arora et al. 2006, 2008; Choi et al. 2010). So far, product liability – the focus of our study – has not been an important policy instrument with respect to software defects (e.g., Childers 2008, Scott 2008). In a recent contribution, Lam (2016) considers both regulation and liability in a framework in which software firms and software consumers can invest in reducing expected harm, finding that a combination of regulation and partial liability is socially optimal for the setup. The fact

[5] Other recent contributions highlighting setups in which this irrelevance does not hold include Daughety and Reinganum (2014) who consider the case of harm rising with the level of consumption, and Baumann et al. (2016, 2018) who analyze the choices of firms with market power facing consumers with heterogeneous levels of harm.

[6] Marino (1997) is interested in the design of the perfect recall when firms have private information about their ability to produce safe goods and are subject to imperfect product liability. Welling (1991) also discusses harm mitigation ex-post. However, she focuses on a firm's decision about whether to release information about product risk after sale, and consumers' related decisions regarding a discontinuation of product use.

that full liability is not optimal depends critically on the software consumers' ability to address expected harm. We arrive at a similar finding for a very different reason.

1.3 Outline

We lay out the model in Section 2 and describe both the equilibrium and social welfare considerations in Section 3. In Section 4, we discuss our framework and results in the light of previous contributions and consider several extensions to our model. Section 5 concludes.

2 The model

Building on Chen and Hua (2012), our model includes a continuum of consumers and one firm.[7]

The firm. The firm chooses product safety, the price per unit of output, and ex-post harm mitigation. Product safety is described by the probability θ that the product is safe, $\theta \in [0, 1)$. Production costs are $C(\theta, q) = k(\theta)q + K(\theta)$, where $k(\theta)$ denotes the variable cost per unit of output, q stands for total output, and $K(\theta)$ represents a fixed cost. Production costs are strictly convex in product safety, i.e., $\partial C/\partial\theta$, $\partial^2 C/\partial\theta^2 > 0$. Only after sale, the firm learns whether the product is safe or risky. When the product is risky, nature draws the level of expected harm h per unit sold from the interval $[\underline{h}, \overline{h}]$ according to the cumulative distribution function $F(h)$ with density $F'(h) = f(h)$. The mean value of expected harm is denoted by $E[h]$ and describes ex-ante expected harm of a risky product. The firm observes the level of expected harm h and may mitigate expected harm after sale.[8] Harm mitigation comes at a cost $\Omega(q) = mq + M$, where m denotes variable cost per unit of output and M represents a fixed cost. Mitigation reduces expected harm from h to $(1 - \eta)h$, $\eta \in (0, 1]$, but also has an adverse impact on consumers' valuation (as explained below). We assume that the firm is held strictly liable for a share γ of the harm consumers incur (see, e.g., Daughety and Reinganum 2006).

[7] In Section 4.1, we explain how our contribution differs from Chen and Hua (2012) in terms of assumptions and results.

[8] Consumers may only observe the individually realized level of harm, making it impossible for the consumer to perfectly infer the expected harm that the firm used in its harm mitigation choice.

Consumers. The population of consumers is normalized to one. Consumers differ in their valuation v of the product, where $v \in [\underline{v}, \overline{v}]$ according to the cumulative distribution function $G(v)$ with density $G'(v) = g(v)$. We denote by $E[v]$ the mean of consumers' valuation. The function G is characterized by a non-decreasing hazard rate $g(v)/[1 - G(v)]$. When the firm mitigates harm, a consumer's valuation of the product is reduced from v to $(1 - \tau)v$, where $\tau \in [0, \eta)$. We assume that $\underline{v} \geq \overline{h}$, implying that continuing to consume the product is always preferred even if the product is risky. In addition, we suppose $\tau E[v] + \Omega(1) < \eta\overline{h}$, thereby ensuring that mitigation of harm is socially beneficial at least for some high expected harm levels when all consumers are served by the firm (i.e. when $q = 1$).

Timing. In Stage 1, the firm chooses product safety and price. Consumers' demand depends on the observable level of product safety, price, and the firm's harm mitigation as anticipated by consumers. In Stage 2, the firm first learns whether the product is risky and the level of expected harm when the product is risky. It then decides about harm mitigation. Afterwards, harm may be realized; when harm occurs, compensatory payments are made according to the liability system in place.

3 Equilibrium

We consider subgame-perfect equilibrium play in two scenarios. First, in Section 3.1, we derive key insights regarding social welfare and the relationship between product safety and harm mitigation when the firm chooses to serve all consumers. Serving all consumers is profit maximizing for the firm when the minimum valuation $\underline{v}$ is sufficiently large when compared to production costs (see, e.g., Hua and Spier 2018). Afterwards, we consider the case in which the monopolist finds lower output optimal and highlight the interaction between output levels, product safety, and harm mitigation (Section 3.2).

3.1 Full market coverage

Stage 2: Mitigation. When the firm chooses whether or not to mitigate harm, it knows the product's risk (i.e. the relevant level of expected harm). The firm prefers mitigation when the sum of mitigation costs and remaining expected liability payments falls short of expected liability payments without mitigation,[9]

$$\Omega + (1-\eta)\gamma h \leq \gamma h.$$

The firm's comparison of cost levels yields a critical level for the expected harm,

$$h_M = \min\left\{\overline{h}, \frac{\Omega}{\eta\gamma}\right\},$$

such that the subgame-perfect harm mitigation choice consists of mitigating harm when $h \geq h_M$. The benefit from mitigating harm as perceived by the firm (i.e., the reduction in expected liability payments) increases with the extent of loss shifting. In fact, the incentive stemming from liability is insufficient to induce harm mitigation even for the highest expected harm level when $\gamma < \gamma_n$ with

$$\gamma_n = \frac{\Omega}{\eta\overline{h}}.$$

Thus, we obtain:

Lemma 1 *The subgame-perfect critical harm level h_M decreases with the level of liability when $\gamma > \gamma_n$. The firm will never mitigate harm when liability falls short of γ_n.*

Stage 1: Product safety and price. Consumers observe product safety and anticipate the firm's mitigation choice in Stage 2. With full market coverage, the profit-maximizing price p is equal to the willingness to pay of the consumer with the smallest product valuation, that is,

$$p = \underline{v} - (1-\theta)\left\{(1-\gamma)H(h_M) + [1-F(h_M)]\,\tau\underline{v}\right\} \tag{1}$$

where

$$H(h_M) = E[h] - \eta \int_{h_M}^{\overline{h}} h dF(h)$$

is the ex-ante expected harm from a risky product given the firm's subgame-perfect mitigation choice from Stage 2. The marginal consumer's willingness to pay incorporates the costs resulting from a risky product, which consist of uncompensated harm and consumption benefits lost when the firm mitigates harm. Using the price level specified in (1), the firm's ex-ante expected profits can be stated as

$$\pi = \underline{v} - C(\theta) - (1-\theta)\left\{H(h_M) + [1-F(h_M)]\,(\Omega + \tau\underline{v})\right\}. \tag{2}$$

[9]To ease notation in this section, we denote mitigation costs by Ω instead of $\Omega(1)$ and production costs by $C(\theta)$ instead of $C(\theta, 1)$.

With observable product safety, liability is relevant to the firm's profits only via its influence on the firm's mitigation choice in Stage 2 (i.e., the level of h_M). The firm maximizes expected profits by choosing the level of product safety. As the threshold h_M is independent of product safety, the firm's first-order condition results as[10]

$$\frac{d\pi}{d\theta} = \frac{\partial \pi}{\partial \theta} = -\frac{\partial C(\theta_M)}{\partial \theta} + \{H(h_M) + [1 - F(h_M)] (\Omega + \tau \underline{v})\} = 0. \tag{3}$$

At the profit-maximizing level of product safety θ_M, marginal costs of safety are set equal to the sum of the increase in the marginal consumer's willingness to pay and the savings in both expected liability payments and mitigation costs.

Liability and profits. The firm's ex-ante expected profits depend on liability only because its level influences the subgame-perfect harm mitigation choice (see equation (2)). If the firm could commit to a rule for harm mitigation before purchase decisions are made, ex-ante expected profits would be independent of the level of liability. From[11]

$$\frac{\partial \pi}{\partial h_M} = -(1 - \theta_M) f(h_M) \{\eta h_M - (\Omega + \tau \underline{v})\}$$

we deduce that the harm mitigation choice maximizing ex-ante expected profits consists of mitigating harm when $h \geq h_\pi$, where[12]

$$h_\pi = \frac{\Omega + \tau \underline{v}}{\eta}. \tag{4}$$

This critical harm level sets mitigation's benefits (in terms of the reduction in expected harm) equal to the firm's total mitigation costs (consisting of both mitigation costs and the marginal consumer's loss of consumption benefits), that is, it solves $\eta h_\pi = \Omega + \tau \underline{v}$. In Stage 1, the firm internalizes the full surplus of the marginal consumer via its price setting.

In our framework, the critical harm level h_π is attained despite the firm's lack of commitment power when the level of liability is equal to

$$\gamma_\pi = \frac{\Omega}{\Omega + \tau \underline{v}} \in (0, 1). \tag{5}$$

[10]The second-order condition for a profit maximum is fulfilled.

[11]The second-order conditions for a local profit-maximum are fulfilled as $\partial^2 \pi / \partial (h_M)^2 = -(1 - \theta_M) f(h_\pi) < 0$ at $h_M = h_\pi$ and $\partial^2 \pi / (\partial \theta \partial h_M) = 0$.

[12]The ranking $h_\pi < \overline{h}$ is assured by the assumption $\tau E[v] + \Omega < \eta \overline{h}$.

Full liability ($\gamma = 1$) induces excessive mitigation incentives as the firm neglects the marginal consumer's loss of consumption benefits; no liability ($\gamma = 0$) signifies that the firm will never mitigate as harm is fully borne by consumers. In Stage 2, the firm ignores the marginal consumer's benefit loss (introducing a tendency for excessive mitigation) and the effect on expected harm to the extent that the firm is not legally responsible for harm (introducing a tendency for too infrequent mitigation). With liability at γ_π, both effects are of the same magnitude at the ex-ante profit-maximizing critical harm level, as

$$(1-\gamma_\pi)\eta h_\pi = \frac{\tau \underline{v}}{\Omega + \tau \underline{v}} \eta h_\pi = \tau \underline{v}$$

implying that the firm is committed to the harm mitigation choice that maximizes ex-ante profits. The level of liability γ_π aligns the firm's subgame-perfect harm mitigation choice with the harm mitigation choice maximizing ex-ante profits. We summarize in:

Lemma 2 *With full market coverage, the firm's ex-ante expected profits are at a maximum for* $\gamma = \gamma_\pi$.

Proof. We have

$$\frac{d\pi}{d\gamma} = \frac{\partial \pi}{\partial \theta}\frac{d\theta_M}{d\gamma} + \frac{\partial \pi}{\partial h_M}\frac{dh_M}{d\gamma}$$

where $\partial\pi/\partial\theta = 0$ due to the firm choosing product safety in Stage 1 and $\partial\pi/\partial h_M = 0$ for $\gamma = \gamma_\pi$. For $0 < \gamma < \gamma_n$, $d\pi/d\gamma = 0$ as harm mitigation is not affected by a marginal increase in liability. For $\gamma_n < \gamma < \gamma_\pi$, $d\pi/d\gamma > 0$ as $h_M > h_\pi$, resulting in $\partial\pi/\partial h_M < 0$, and $dh_M/d\gamma < 0$. For $\gamma = \gamma_\pi$, we have $d\pi/d\gamma = 0$. For $\gamma_\pi < \gamma$, $d\pi/d\gamma < 0$ as $h_M < h_\pi$, resulting in $\partial\pi/\partial h_M < 0$, and $dh_M/d\gamma < 0$. ■

Liability, product safety, and harm mitigation. We are now in the position to analyze the relationship between liability, product safety, and harm mitigation. From (3) and (4), we obtain

$$\frac{d\theta_M}{d\gamma} = \frac{f(h_M)}{\partial^2 C(\theta_M)/\partial\theta^2}\eta\left[h_M - h_\pi\right]\frac{dh_M}{d\gamma}. \tag{6}$$

The firm is (weakly) more inclined to mitigate harm when the level of liability is higher (i.e. $dh_M/d\gamma < 0$ for $\gamma > \gamma_n$; Lemma 1). In contrast, the level of product safety may increase or decrease with the level of liability. A marginal increase in the level of liability from a level between γ_n and γ_π implies that the risky-product state becomes less costly for the firm (as the difference between the subgame-perfect harm threshold, h_M, and the one that maximizes ex-ante profits, h_π, is reduced). Lower expected costs in the risky-product state mean a lower marginal benefit of product safety. In contrast, a marginal increase in the level of liability from a level above the one that maximizes ex-ante profits, γ_π, signifies higher costs in the risky-product state (as h_M moves away from h_π). The marginal benefit of product safety investments increases as a result. In other words, product safety and harm mitigation are *substitutes* at low levels of liability and *complements* at high levels of liability. We have:

Proposition 1 *Assume full market coverage. (i) Product safety is u-shaped in the level of liability, with a minimum attained at the profit-maximizing level of liability (i.e., at $\gamma = \gamma_\pi$). (ii) Product safety and harm mitigation are substitutes when liability falls short of the the profit-maximizing level (i.e., when $\gamma \in (\gamma_n, \gamma_\pi)$) and complements at higher levels of liability (i.e., when $\gamma \in (\gamma_\pi, 1)$).*

Proof. Follows from (6) in combination with (4) and (5). ■

Liability and social welfare. Social welfare in the market equilibrium is given by

$$SW = E[v] - C(\theta_M) - (1 - \theta_M)\{H(h_M) + [1 - F(h_M)](\Omega + \tau E[v])\}. \tag{7}$$

Comparing this expression to the firm's profit equation in (2), we find that the average consumer's product valuation replaces that of the marginal consumer. This difference is key for comparing ex-ante profit-maximizing and welfare-maximizing choices.

To maximize welfare, harm should be mitigated if harm exceeds a critical threshold h_W, where

$$h_W = \frac{\Omega + \tau E[v]}{\eta}.$$

The difference between the socially optimal threshold h_W and the subgame-perfect one (i.e., h_M) results from both the firm's neglecting consumption benefit losses and the firm's focusing exclusively on expected liability payments instead of expected harm. However, the level of liability can be used to align the two critical values. In fact, we obtain $h_M = h_W$ when

$$\gamma = \gamma_W = \frac{\Omega}{\tau E[v] + \Omega} \leq \gamma_\pi.$$

The ranking of the liability levels, $\gamma_W \leq \gamma_\pi$, results from the social planner's concern for the average consumer and the firm's concern for the marginal consumer (such that $\gamma_W = \gamma_\pi$ only when consumers are symmetric, i.e., when $E[v] = \underline{v}$). We summarize in:

Lemma 3 *Assume full market coverage. The firm's incentives to mitigate harm in Stage 2 are socially excessive (suboptimal) with full (no) liability. The liability share* $\gamma_W \in (0,1)$ *induces socially optimal harm mitigation incentives. This share is lower than the profit-maximizing one* γ_π *when consumers have heterogeneous consumption valuations (i.e,* $E[v] > \underline{v}$*).*

For a given level of $h_M < \overline{h}$ in Stage 2, the social planner's marginal benefit of product safety *exceeds* the firm's marginal benefit in Stage 1 when $E[v] > \underline{v}$. This results because the firm does not internalize the full expected social costs of a risky product. More precisely, whereas the firm considers the loss in revenue arising from the marginal consumer's anticipation of consumption benefit losses due to harm mitigation by the firm, a social planner considers the loss in average consumption benefits.

Lemma 4 *Assume full market coverage. For a given critical harm level* $h_M < \overline{h}$*, the profit-maximizing level of product safety falls short of the socially optimal level of product safety independent of the level of liability when* $E[v] > \underline{v}$*. When consumers are symmetric, product safety choices of the social planner and the firm are consistent.*

Proof. Making use of (3) to evaluate $\partial SW/\partial\theta$ in the market equilibrium, we obtain

$$\frac{\partial SW}{\partial \theta} = [1 - F(h_M)]\,\tau\,[E[v] - \underline{v}]\,.$$

■

We can now infer some properties of the socially optimal level of liability. The liability level γ_W aligns the subgame-perfect harm mitigation choice with the socially optimal harm mitigation choice in Stage 2 (see Lemma 3). The firm's choice of product safety is always suboptimal for heterogeneous consumers (see Lemma 4) and can be raised in the range $\gamma < \gamma_\pi$ by reducing the level of liability (see Proposition 1). Starting from the level of liability that induces efficiency in Stage 2, $\gamma = \gamma_W$, a marginal decrease in the liability share increases both product safety investments in Stage 1 and the critical harm level in Stage 2, but the implied change in harm mitigation is negligible for welfare.[13]

This leads to the result:

[13] It holds that $dSW/d\gamma < 0$ for $\gamma \in [\gamma_W, \gamma_\pi]$ since harm mitigation is excessive and product safety is too low from a welfare perspective. By a continuity argument, $dSW/d\gamma < 0$ will hold for values slightly lower (higher) values than γ_W (γ_π) as well.

Proposition 2 *Assume full market coverage. For symmetric consumers, social welfare is maximal when the level of liability induces socially optimal harm mitigation (i.e., when $\gamma = \gamma_W$). With heterogeneous consumers, starting at the level of liability that induces socially optimal harm mitigation, a marginal reduction in liability increases welfare.*

Proposition 2 does not unambiguously pin down socially optimal liability. With full-market coverage, the social planner is concerned about both the level of product safety investments and the harm mitigation choice. The firm's subgame-perfect harm mitigation choice is socially optimal when $\gamma = \gamma_W$ whereas, for any mitigation choice described by h_M, the product safety level implemented by the firm is less than the socially optimal one. As a result of this shortfall in product safety investments, a marginally lower level of liability is socially dominant to the level leading to socially optimal harm mitigation in Stage 2 (because this change in liability increases product safety investments). With product safety being u-shaped with a minimum attained at $\gamma = \gamma_\pi > \gamma_W$, it follows that levels of product safety investments higher than the one attained at γ_W can possibly be induced by implementing either $\gamma < \gamma_W$ or some $\gamma > \gamma_\pi$. Whereas the former liability levels imply that mitigation is used too infrequently from a social point of view, the latter liability levels bring about socially excessive harm mitigation. Although it is not guaranteed that social welfare is concave in the firm's liability share without additional assumptions, some features seem to convey that socially optimal liability is rather some level $\gamma < \gamma_W$ than some $\gamma > \gamma_\pi$. To obtain levels of product safety investments higher than the one attained with γ_W requires a small departure from γ_W when liability is reduced starting from γ_W whereas it requires a large departure from γ_W when liability is raised starting from γ_W (because safety investments first decrease until liability reaches the level $\gamma_\pi > \gamma_W$). In the interval (γ_W, γ_π), social welfare decreases in the firm's liability share as both the product safety investment level and subgame-perfect harm mitigation choice move further away from socially optimal levels. This suggests that deviating from γ_W to lower levels of γ instead of to levels of $\gamma > \gamma_\pi$ is socially preferable. We argue that socially optimal liability will be greater than zero. Harm mitigation is socially desirable at least for high realizations of expected harm by assumption and will not happen when liability is zero.

3.2 Less than full market coverage

In this section, we explore how the firm's output choice is influenced by the level of liability and how output interacts with product safety and harm mitigation. We denote by v_M the consumption valuation of the marginal consumer, implying a level of output $q = q(v_M) = 1 - G(v_M)$ and a mean valuation of *active* consumers equal to $E[v|v \geq v_M]$.

Stage 2: Mitigation. The reduction in expected liability obtained by mitigation is proportional to the level of output. In contrast, mitigation costs increase less then proportionally with output if some costs are fixed (i.e., when $M > 0$). Comparing the savings in expected liability (i.e., $\gamma\eta hq$) with mitigation costs (i.e., $\Omega(q) = mq + M$), the critical level of harm results as

$$h_M = \min\left\{\overline{h}, \frac{\Omega(q)/q}{\gamma\eta}\right\}. \tag{8}$$

We thus find that:

Lemma 5 *Higher output (weakly) strengthens firm's mitigation incentives (i.e., $\partial h_M/\partial q \leq 0$).*

Proof. The claim follows from

$$\frac{\partial h_M}{\partial q} = -\frac{M}{q^2\gamma\eta}$$

when $h_M = \frac{\Omega(q)/q}{\gamma\eta}$ and $\frac{\partial h_M}{\partial q} = 0$ otherwise. ■

For every output level q, a level of liability exists that aligns the subgame-perfect critical harm level in Stage 2 with the one that maximizes ex-ante profits or social welfare,

$$\gamma_\pi(q) = \frac{\Omega(q)}{\tau v_M q + \Omega(q)} > \gamma_W(q) = \frac{\Omega(q)}{\tau E[v|v \geq v_M]q + \Omega(q)}.$$

Stage 1: Product safety and the level of output. The firm's profits amount to

$$\pi = [v_M - (1-\theta)\{H(h_M) + [1 - F(h_M)]\,\tau v_M\}]\,q - C(\theta, q) - (1-\theta)\,[1 - F(h_M)]\,\Omega(q) \tag{9}$$

With full market coverage, the firm sets the price according to the marginal consumer's willingness to pay, knowing that the critical harm level in Stage 2 is not affected by the firm's price-setting in Stage 1. This is fundamentally different in the present scenario, because the pricing decision determines output which in turn is important for the critical harm level when harm mitigation involves some fixed costs (i.e. $M > 0$). The relationship between the critical harm level and output is important for the firm because the firm's subgame-perfect harm mitigation choice does not maximize ex-ante expected profits when $\gamma \neq \gamma_\pi(q)$. We highlight this indirect effect as the first term in the corresponding first-order condition,[14]

$$\frac{\partial \pi}{\partial v_M} = -\frac{\partial \pi}{\partial h_M}\frac{\partial h_M}{\partial q} g(v_M) + \frac{\partial C(\theta_M, q)}{\partial q} g(v_M) + q\left(1 - (1-\theta_M)\left[1 - F(h_M)\right]\tau\right)$$
$$- g(v_M)\left[v_M - (1-\theta_M)\left\{H(h_M) + \left[1 - F(h_M)\right](\tau v_M + \Omega'(q))\right\}\right] = 0. \quad (10)$$

Except for the indirect effect (first term in (10)), all expressions in condition (10) are standard terms in a monopolist's first-order condition with respect to output. The decrease in output implied by an increase in the marginal consumer's valuation v_M leads to a saving in production costs (second term), allows for an increase in revenues due to the increase in price (third term) but lowers profits as the profit margin is foregone for consumers no longer served (second line in (10)). The indirect effect signifies that the firm's choice of output also reflects strategic concerns as higher output allows the firm to commit to more likely harm mitigation (as $\partial h_M/\partial q < 0$ when mitigation costs include a fixed component). This strategic concern increases (decreases) the incentives to expand output when the level of liability is below (above) the level that maximizes ex-ante profits. For example, when liability is low, the subgame-perfect harm mitigation choice is generated by a threshold greater than the harm mitigation choice maximizing ex-ante profits. Higher output in this case brings about a better alignment by decreasing the subgame-perfect harm mitigation threshold.

Predicting how the profit-maximizing level of output changes when firm liability increases is difficult even for a given level of product safety (see Appendix A.6 for the corresponding comparative statics). A higher level of liability will induce a lower harm threshold h_M and thereby increase the probability of harm mitigation and a consumption benefit loss. This implies that increasing v_M has a smaller positive effect on the markup per unit of output, which lowers the monopolist's incentive to curb output. At the same time, higher liability might alleviate (aggravate) the firm's commitment problem in the sense of pushing h_M closer to (further away from) the level that maximizes ex-ante profits. On the one hand, this alters the firm's profit margin relevant for the computation of marginal revenue and, on the other

[14] Second-order conditions are assumed to be fulfilled. The non-decreasing hazard rate for consumer valuation would guarantee concave revenues in a model without harm mitigation. The possibility of harm mitigation and the presence of fixed production costs complicate second-order conditions with endogenous output. In the numerical examples presented at the end of this section, the maximum is always well-specified.

hand, alters the incentive to use adjustments in output to commit to a specific critical harm level.

The first-order condition for product safety mirrors the one discussed in Section 3.1 with marginal benefits and marginal costs from higher product safety investments evaluated at the level of output q,

$$\frac{\partial \pi}{\partial \theta} = -\frac{\partial C(\theta_M, q)}{\partial \theta} + q \left\{ H(h_M) + [1 - F(h_M)] \left(\tau v_M + \frac{\Omega(q)}{q} \right) \right\} = 0. \tag{11}$$

How product safety changes with the level of output depends on the assumptions regarding the firm's cost structure (for comparative statics refer to Appendix A.7). When neither product safety nor mitigation costs include a fixed component, higher output affects the firm's product safety investment only via the decrease in the marginal consumer's valuation. As this decrease in v_M reduces the loss in marginal consumption benefit in the risky-product state, it lowers the firm's product safety investment incentives. Otherwise, without fixed costs, both marginal benefits and marginal costs of lowering the probability of the risky-product state are proportionally varied by output, and output has no effect on the subgame-perfect harm mitigation choice. When production costs include fixed costs, a higher output level accords higher product safety via scale economies. When harm mitigation involves fixed costs, there are two aspects to be considered. First, higher output provides for relatively lower product safety incentives as the benefits from preventing the risky-product state increase less than proportionally with output. Second, in this case, output strategically influences the subgame-perfect harm mitigation choice, bringing h_M closer to the firm's optimal level h_π. This implies that the benefit from preventing the risky-product state is reduced.

Our considerations above point to a complex interaction of the endogenous variables and liability. To facilitate understanding of the various implications, we turn to the results from more than fifty numerical simulations.

Numerical simulations. For all of our simulations, we subscribe to the following assumptions: Harm mitigation costs are as introduced in Section 2, where $m, M \in \{0, 1/30, 1/15\}$. Product safety costs are specified as

$$C_I(\theta, q) = (c + k\theta^2)q + K\theta^2.$$

We consider $c \in \{0.5, 1, 1.5\}$ and $k, K \in \{0, 0.1, 0.2\}$. The consumers' valuation v is distributed

Table 1: Parameter Values for Endogenous Output Simulations

	η	τ	c	k	K	m	M	z_h	z_v
Baseline	0.9	0.1	1	0.1	0.1	1/30	1/30	1	0.5
Alternative Levels	0.8	0.05	1.5	0, 0.2	0, 0.2	0, 1/15	0, 1/15	0, 0.5	0, 1

on the interval $\left[2, 2 + \frac{2}{1+z_v}\right]$ according to the density function

$$g_I(v) = \frac{1+z_v}{2}\left(2 - (v-2)(1+z_v) + 2z_v((v-2)(1+z_v) - 1)\right),$$

which exhibits a non-decreasing hazard rate for the z_v-values considered. The expected harm h is distributed on the interval $\left[0, \frac{1}{1+z_h}\right]$ according to the density function

$$f_I(h) = (1+z_h)\left(2 - 2h(1+z_h) + 2z_h(2h(1+z_h) - 1)\right).$$

In our simulations, we focus on $z_v, z_h \in \{0, 1/2, 1\}$. The density functions g_I and f_I permit consideration of skewed and uniform distributions while maintaining the expected value for the valuation at $E[v] = 8/3$ and the ex-ante expected harm caused by a risky product at $E[h] = 1/3$, respectively.[15] When $z_v = 1/2$, the distribution of consumer valuations is uniform with density $g_I = 3/4$. When $z_v = 0$ $(= 1)$, the distribution function is a right- (left-) skewed triangle. The same is true for the distribution of expected harm where $f_I = 3/2$ for $z_h = 1/2$.

In our presentation of findings from the numerical simulations, we will first attend to one baseline case in some detail. The parameter configuration used for the baseline scenario as well as the parameters additionally included in our other simulations are described in Table 1. The results for the baseline case are qualitatively representative for the majority of our simulations. Afterwards, we discuss the main insights derived from our 54 other simulations, where our focus is on the key results regarding the ranking of socially optimal and profit-maximizing liability levels as well as how product safety investments depend on liability.

For the baseline case, in the first panel in Figure 1, we depict the firm's critical harm level h_M (bold line) and the socially optimal critical level h_W (dashed line) for equilibrium output at this level of liability. The firm mitigates harm for some realizations of expected harm when $\gamma > \gamma_n \approx 0.16$. Around $\gamma = 0.21 = \gamma_W$, the firm's subgame-perfect harm mitigation choice is aligned with the socially optimal harm mitigation choice. As described in Figure 2 which

[15]We gratefully acknowledge the suggestion by an anonymous reviewer to proceed in this way.

depicts relative profits (bold curve), the profit-maximizing level of liability is $\gamma_\pi = 0.25$ and thus markedly higher than the level at which the subgame-perfect harm choice aligns with the socially optimal one. The second panel in Figure 1 describes how output varies with liability. For levels of liability above γ_n but below the one that maximizes the firm's ex-ante expected profits, a relatively high level of output is used strategically to improve the own harm mitigation choice. An imposed level of liability closer to the ex-ante profit-maximizing liability level reduces the tendency towards output distortions. This helps to explain that there is a segment with decreasing output levels. In the third panel in Figure 1, we find that the profit-maximizing product safety investments initially decrease when liability increases beyond the minimum value of γ_n. The minimal product safety level is reached in the neighborhood of the ex-ante profits maximizing level, γ_π.[16] Afterwards, product safety increases. Our baseline case thus shows that, also without full market coverage, product safety and harm mitigation can be substitutes for one range of liability – product safety decreases with γ while the likelihood of mitigation increases with it when $\gamma \in (0.16, 0.25)$ – and complements for others (for example, when $\gamma \in (0.25, 1)$). In other words, product safety is a u-shaped function of the level of liability (as was true for the full-market coverage scenario, Proposition 1).

Figure 2 also reports relative social welfare as a function of liability (dashed curve). Importantly, we find that the pattern of critical liability thresholds described in Section 3.1 for the case of full-market coverage – see Proposition 2 – stays intact in our baseline simulation with endogenous output as we have $\gamma^* = 0.175 < \gamma_W = 0.21 < \gamma_\pi = 0.25$.

INSERT FIGURE 1 ABOUT HERE

INSERT FIGURE 2 ABOUT HERE

We conclude our discussion of the baseline case by focusing on the role of the endogeneity of output for socially optimal liability. We have explained above that the fact that the firm chooses

[16] When output is endogenous, the level of liability that maximizes ex-ante expected profits and the one minimizing profit-maximizing product safety investments may not coincide. This contrasts with full-market coverage results.

output is important because the firm can use output as a commitment device for later harm mitigation when some harm mitigation costs are fixed. To assess the impact of the endogeneity of output on the socially optimal liability, we calculate the level of socially optimal liability when only product safety and harm mitigation are endogenous while the level of output is fixed as a benchmark. For comparability, this fixed level of output is the one that results under socially optimal liability in the case with endogenous output. For our baseline scenario, we find that this *hypothetical* level of liability that maximizes welfare is given by $\gamma^*_{EXO} = 0.205$, and is thus higher than the socially optimal level of liability derived under the endogenous output assumption. This difference is intuitive as, in the case considered, the planner is exploiting the firm's commitment incentive by reducing the level of liability in order to obtain a greater level of equilibrium output.

Starting from the detailed consideration of the baseline case, we can make several observations regarding the insights generated by our numerical simulations described in detail in Appendix A.8. Probably the most important observation is that we obtain the ranking $\gamma^* < \gamma_W < \gamma_\pi$ almost always when $M > 0$ and $m \geq 0$, that is, when at least some harm mitigation costs are fixed. We use the qualifier *almost* because in one out of 48 cases with $M > 0$ and $m \geq 0$, we obtain the ranking $\gamma_W < \gamma^* < \gamma_\pi$. In other words, in this special case, the socially optimal level of liability is still less than the one maximizing ex-ante expected profits, but the liability that aligns the subgame-perfect harm mitigation choice with the socially optimal one results as the minimum of the three critical levels (see Line 43 in our Table A.8). In all simulations that include positive fixed costs of harm mitigation, we obtain that $\gamma^* < \gamma^*_{EXO}$, that is, the endogeneity of output reduces the socially optimal liability level in all of our simulations when harm mitigation includes fixed costs. If we assume that harm mitigation causes only variable cost, that is, if we consider $M = 0$ and $m > 0$ instead of $M > 0$ and $m \geq 0$ results change. In these scenarios, we obtain $\gamma^* \approx \gamma_\pi$, $\gamma^* > \gamma_W$, and $\gamma^* > \gamma^*_{EXO}$. Without fixed costs of harm mitigation, the firm cannot use higher output levels to commit to more frequent harm mitigation at low liability levels. In our simulations, output in these circumstances is high for rather high levels of liability, explaining the relatively higher socially optimal liability.

With regard to the level of product safety investments, we obtain a u-shaped pattern of some kind in all of our simulations (i.e., with or without fixed costs of harm mitigation). This comes despite the fact that the scenarios with only variable mitigation costs mirror the assumptions on harm mitigation costs made by Chen and Hua (2012) who report the possibility of an *inverted* u-shape. The contrast to Chen and Hua (2012) stems from our incorporation of potential consumption benefit losses resulting from harm mitigation. Indeed, absent consumption benefit losses (i.e., when $\tau = 0$), the rear upward sloping part of the u-shape would disappear. The inverted u-shape in Chen and Hua (2012) is due to an output effect caused by fixed costs of product safety investments. Such an output effect is present in our simulations as well and – in contrast to the baseline simulation – can lead to product safety investments that first increase in liability before showing the typical u-shape. This is the case in 16 out of our 55 simulations. The 16 simulations all necessarily include fixed product safety costs $K > 0$ (see Table A.8).

4 Discussion

In this section, we will first relate our paper to the contribution by Chen and Hua (2012) as they similarly consider a monopolistic firm applying ex-ante and ex-post measures to prevent harm. Next, we briefly discuss the consequences of important modifications in our modeling assumptions. We delegate the formal derivation of results to the appendix.

4.1 Relationship to Chen and Hua (2012)

The present paper considers a scenario in which the firm can use an ex-ante safety measure to lessen the likelihood that the product is risky and an ex-post safety measure to be used after product risks materialize. Chen and Hua (2012) (CH in the following discussion) consider a similar setup with some important differences in modeling assumptions.

CH assume that product safety implies a fixed cost and no variable cost, whereas remedial action is associated with a constant per unit cost and no additional fixed cost. We consider more general cost functions and highlight the role of the cost structure for results. CH's cost structure assumption makes the ex-post remedial effort independent of first-stage decision-making. In contrast, we allow mitigation costs to have a fixed component, in which case the level of output determined in Stage 1 has a commitment value with regard to the mitigation choice in Stage 2 (see Lemma 5). Our numerical simulations highlight that these strategic concerns can be important.

However, the most important distinction in terms of assumptions is that we consider harm mitigation by the firm that reduces the product value for consumers. CH assume instead that remedial action is free of cost for consumers. The loss in consumption benefits is both demonstrably realistic and economically significant as exemplified by the examples presented in the introduction such as the impairment of product use by software updates or temporary non-availability of the product during repair. The different assumptions are drivers of major distinctions when it comes to *results*, which we will now briefly discuss.

A key result by CH (their Proposition 1) is showing that product safety decreases with the level of liability when firm liability is high but may increase with it when firm liability is low (i.e., that product safety may describe an *inverted* u-shape). Their finding results from the presence of a "substitution effect" and an "output effect". To explain, an increase in the level of liability intensifies the use of harm mitigation which substitutes for product safety (the "substitution effect"). At the same time, higher liability leads to an increase in the profit-maximizing level of output which encourages product safety via scale economies (the "output effect"). In this way, their result about the inverted u-shape hinges on the "output effect" being dominant for low levels of liability. This implies that, for fixed output, the two instruments are necessarily substitutes in CH's setup. In contrast, product safety is u-shaped in our setup for fixed output (see Proposition 1). Thus, in our setup, the finding of product safety and harm mitigation being either substitutes or complements does not depend on additional effects induced by changes in output. The expected costs from the risky-product state are minimized for an interior level of liability, implying that increasing liability at high (low) levels raises (lowers) marginal benefits of product safety. Our finding results from the consumption benefit loss due to harm mitigation. An effect similar to CH's "output effect" exists in our analysis with less than full-market coverage. Still, even in this case, our numerical simulations illustrate that the relationship between product safety and harm mitigation may be just the opposite of what CH find: in our analysis the two instruments are substitutes at low levels of liability and complements at high levels; in CH two instruments are complements at low levels of liability and substitutes at high levels.

In both papers, the firm prefers some product liability in order to have mitigation incentives in Stage 2. In CH, the level of liability that maximizes ex-ante profits is full liability. In our contribution, the profit-maximizing level of liability is strictly less than one. This difference again originates from our assumption about harm mitigation causing losses in consumption benefits (i.e., this result also manifests itself when we maintain CH's assumptions about cost functions).

Finally, in CH, the profit-maximizing product safety level is aligned with the socially optimal one for a fixed critical harm level. In contrast, for a fixed critical harm level, the profit-maximizing product safety level falls short of the socially optimal one in our model. This distinction is again due to our assumption of harm mitigation leading to losses in consumption benefits (and, thus, also shows when we maintain CH's assumptions about cost functions). In our setup, the firm incorporates this aspect with respect to the marginal consumer whereas it would be socially adequate to take it into account for the average consumer (see Lemma 4).

4.2 Robustness to Varying Modeling Assumptions

Consumer precaution. In our analysis, we consider both product safety and harm mitigation as means of the firm to address expected harm. In the literature on product liability, it is common to assume that the consumer influences the expected harm only by varying the quantity demanded. However, there may be circumstances in which consumers can also influence the ultimate level of expected harm. In a bilateral-care framework, Daughety and Reinganum (2013) show that strict liability with a defense of contributory negligence performs well. We follow the approach of Chen and Hua (2017) and suppose that non-mitigated expected harm can be represented by $h + D(\vartheta)$ where $h > 0$ is defined as before and $D(\vartheta) > 0$ is an additional harm component that can be reduced by consumer care ϑ. Harm mitigation reduces expected harm by $\eta(h + D(\vartheta))$. We consider strict liability with a defense of contributory negligence such that the firm is liable for a share γ of both harm and consumer precaution costs when the consumer was non-negligent and is not at all liable when the consumer was negligent. Assuming this rule, we can show that our main results are robust to the incorporation of consumer precaution. When the negligence standard directed at consumers depends on whether the firm mitigated harm, consumers' precautions are efficient when they implement precautions according to the standard. We find that consumers indeed are incentivized to be compliant under the liability rule considered. Given consumers who obey the negligence standard, the firm considers the minimized total losses in the two scenarios – with and without harm mitigation – according to its share in liability which leaves the analysis otherwise unaffected.

Compensating consumers as an additional instrument of the policy maker/firm. Assume that the firm must pay uniform compensation d to consumers when it mitigates harm to provide (imperfect) compensation for the loss in consumption value. Introducing such compensation deters harm mitigation as it becomes more costly for the firm to mitigate harm. Combining both the compensation payment and the firm's liability, the planner can implement any desired critical harm level for mitigation as was also true with liability as the sole policy instrument. When positive compensation payments are used in addition to liability, the level of liability must be increased to maintain a specific subgame-perfect harm mitigation choice. Due to the adjustment in consumers' willingness to pay in anticipation of the compensation payment, the compensation payment is not directly relevant for the firm's ex-ante profits such that the profit equation is still given by (9) where the compensation payment influences only the subgame-perfect harm mitigation choice. However, one important contrast results when compensation payments are used in addition to liability. Since a higher liability level is required to maintain harm-mitigation incentives when both liability and compensation payment are used, we find that higher output is less effective as a commitment device for the firm's subgame-perfect harm mitigation choice when both instruments are used jointly. This holds because the compensation payment dampens the scale effect stemming from harm-mitigation fixed costs. Assuming a liability share lower than the profit-maximizing one (as it generally results for the socially optimal level of liability in our simulations in Section 3.2), the firm will respond to higher liability by reducing output, thereby decreasing welfare. This implies that uniform compensation payments as an *additional* policy instrument do not guarantee higher welfare. In contrast, the firm may use the instrument of a compensation payment to solve its commitment problem because, by using this instrument, the firm can predetermine any subgame-perfect harm mitigation choice.[17]

[17] The firm prefers monetary compensation over in-kind compensation (such as the provision of a replacement vehicle during a car's repair). The reason is that, in order to influence its mitigation choice in Stage 2, the firm has an incentive to distort the level of in-kind compensation away from the optimal level of the marginal consumer. This distortion reduces the marginal consumer's willingness to pay. In contrast, the monetary compensation is a pure transfer and can thus be varied freely to induce the profit-maximizing harm mitigation choice. The full analysis of the in-kind compensation scenario is available upon request from the authors.

Product differentiation with regard to harm mitigation. We investigate two extensions regarding product differentiation. In the first one, the firm takes liability and the harm mitigation commitment problem as given, as above, but now offers a second product variety without future harm mitigation. In the second extension, the firm can commit to harm mitigation thresholds for two product varieties using contractually determined liability levels. In that context, we investigate how harm mitigation and product differentiation are linked.

Suppose *first* that the firm offers two product varieties, one with future harm mitigation and one without, when subject to a legally mandated liability level γ. The product variety without harm mitigation would be attractive for consumers with a relatively high valuation for the product (as they bear relatively high losses in consumption benefits when the firm mitigates harm). Since consumers of the product variety with harm mitigation have relatively small valuations, the social costs of mitigation in terms of lost consumption benefits are lower relative to the scenario with only one product variety. In response to the availability of the second product variety, a social planner able to dictate product safety, harm mitigation, and the allocation of consumers to product varieties would like to substitute harm mitigation for product safety. In stark contrast, the firm tends to use harm mitigation less in response to the availability of the second variety. The benefit from the reduction in expected liability payments due to harm mitigation is experienced by the firm only for the subset of consumers who actually choose the product variety with harm mitigation. However, mitigation costs are reduced less than proportionally when mitigation costs include fixed costs. In consequence, the firm tends to reduce both harm mitigation ex-post as well as ex-ante product safety (since the risky-product state becomes less expensive for the firm as well).

Second, we investigate a setting in which the firm can offer two product varieties and commit to harm mitigation thresholds by, for example, specifying liability levels in its sales contract. The firm could offer one product variety with a low threshold for harm mitigation and another product variety with a high one. In this case, additional motives may bear on the firm's profit-maximizing harm mitigation choice. To see this, note that there exists asymmetric information about the consumers' valuations and that the firm screens consumers by posting the two product varieties. The consumer indifferent between the two product variants is determined by both the difference in prices of product varieties and the differences in harm mitigation thresholds. Now, if the firm could select harm mitigation thresholds ex ante, it would choose to distort one of the two levels away from the harm mitigation choice that the respective marginal consumer prefers in order to increase profits by a better price discrimination. Specifically, the firm will choose a lower harm threshold (i.e., more likely use of harm mitigation) for the product variety aimed at consumers with lower product valuations. This allows the firm to increase the price of the product tailored to high valuation consumers, for which the harm mitigation threshold is set efficiently for the marginal consumer. Being allowed to specify the liability levels contractually would enable the firm to implement these profit maximizing harm mitigation thresholds. The underlying mechanism is related to that described by Choi and Spier (2014) for the case in which firms use price and compensation levels to screen consumers privately informed about their valuation and their harm level.

Individual mitigation agreements. Our main analysis assumes that harm mitigation applies symmetrically to all units of the product. Suppose instead that mitigation is consumer specific and that, in contrast to the analysis with two product varieties explained above, consumers choose whether mitigation shall apply to their product unit *after* the level of expected harm is realized. In our discussion below, we focus on the case in which the level of expected harm is common knowledge at the beginning of Stage 2.

Two instruments may make consumers consent to harm mitigation. First, the liability system may imply that refusing the firm's offer to mitigate harm entails a lower level of compensation, $\widetilde{\gamma} = \gamma - \Delta$, $0 \leq \Delta \leq \gamma$. Second, the firm may pay a transfer (which will be negative when the firm sells harm mitigation to consumers). The second instrument relates to Spier (2011) who considers a firm's buyback of risky products. Paralleling one of her key results, we find that the firm exercises its market power and thus does not offer its maximal willingness to pay as transfer payment. The firm benefits from any single consumer's acceptance of mitigation according to the reduction in the firm's expected liability payments, which are greater the higher the firm's share of losses and/or the higher the level of expected harm. The consumers' willingness to accept harm mitigation decreases in the level of liability and increases in the level of expected harm. We find that the firm's willingness to pay and the consumers' willingness to accept are symmetrically affected by a change in liability, implying that the share of consumers who accept harm mitigation in the risky-product state is independent of the level of liability. At the earlier stage when the firm decides whether to mitigate harm or not, the critical harm threshold similarly emerges as independent of the level of liability when the liability regime is not providing incentives for consumers.[18] In contrast, if consumers who refuse harm mitigation receive lower compensation (i.e., if $\Delta > 0$), the firm will use harm mitigation more often as the necessary transfer payments to induce consumers' acceptance decrease.

Reputation concerns. In our main analysis, we consider a single interaction between the firm and consumers. Consequently, in Stage 2, the firm incorporated only short-term cost considerations when reasoning about harm mitigation, which implied a commitment problem of the firm regarding the maximization of ex-ante expected profits. As indicated by Polinsky and Shavell (2010), for example, depending on the industry, repeated interactions with consumers are relevant and create reputation concerns for firms. In our setup, with consumers who purchase repeatedly, we may assume that the firm can develop a reputation for following a specific mitigation policy, i.e., adhering a harm threshold regarding the choice of whether to mitigate harm that may deviate from short-term cost considerations. Consumers may play a grim-trigger strategy such that if a deviation from the announced mitigation policy is observed, consumers' willingness to pay is abruptly adjusted to match the short-term profit oriented mitigation policy. We find that the concern for long-run profits may override short-term incentives shaped by the liability system if the firm values future payoffs sufficiently. Accordingly, a credible threat of consumers' disciplining force can help the firm to maximize expected profits. However, whether liability helps the firm to sustain reputation remains an open question since liability affects deviation profits and profits obtained after reputation is lost in opposing directions.[19]

5 Conclusion

Amending a product after sale may be desirable because the modification's impact on the level of the expected harm associated with product use exceeds social costs. Importantly, modifying a product after sale will usually impose costs on consumers on top of the costs directly incurred by

[18]This complements the findings on the irrelevance of product liability in settings of perfect information as described in Hamada (1976) or Shavell (1987, chapter 3), for example.

[19]In a recent theoretical analysis of reputation and product liability Ganuza et al. (2016) establish that product liability may be a substitute or a complement to reputation concerns because product liability may itself make it easier for firms to sustain reputation. In another recent contribution, Chen and Hua (2017) highlight the intricate relation between product liability, reputation, and the intensity of competition.

the firm. It is important for policy makers to understand the extent to which firms acknowledge the costs they impose on consumers by their use of post-sale remedies and how this feeds back into their choice of pre-sale product safety. Clearly, product liability serves an important role in the regulation of the firm's incentives with respect to product safety and harm mitigation. This paper described a monopolist's use of *pre-sale* product safety and *after-sale* harm mitigation when the firm is subject to product liability and can amend the product after sale without having to ask for consumers' consent.

In our framework, the firm neglects consumers' losses when choosing the post-sale remedy. The firm thereby reduces its own ex-ante profits as consumers' willingness to pay is reduced. A specific level of liability between full liability and no liability enables the firm to attain its profit maximum (as this level of liability commits the firm to the harm mitigation choice that the firm's marginal consumer prefers). When liability is lower or higher than the level that the firm desires, a risky product becomes more expensive for the firm leading to higher investments in product safety. Since a higher level of liability always induces a more frequent post-sale remedy use by the firm, it results from this that product safety and harm mitigation are substitutes for low levels of liability whereas they are complements for high levels. Furthermore, we establish that, if liability differs from the level that maximizes the firm's ex-ante profits, the firm may strategically adjust its own output to steer future use of the post-sale remedy.

The socially optimal level of liability trades off guiding the firm's use of the post-sale remedy on the one hand with incentivizing product safety on the other. Given that harm mitigation and product safety are substitutes for low levels of liability, we find that reducing liability from the level that induces socially optimal harm mitigation after sale may be desirable in order to induce higher product safety. Overall, our study highlights that – potentially high – losses of consumption benefits may argue against using high levels of liability to push firms toward frequent ex-post harm mitigation.

The present paper used a very simple setup to highlight the key mechanisms involving the loss of consumption benefits resulting from firms' use of post-sale remedies. We also discuss several extensions, but there are clearly more aspects of potential relevance. For example, the argumentation presented builds on the assumption that product safety is observable. When there is asymmetric information about the level of product safety, signaling via price level may offer information to consumers about the level of product safety and the firm's planned use of harm mitigation. Asymmetric information about product safety can thus be an interesting extension. Similarly, the consideration of other competitive settings will probably yield interesting additional insights.

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A Appendix

In this appendix, we derive formal results for the extensions to our main analysis presented in Section 4.2. In addition, some comparative statics results are described.

A.1 Consumer precautions

Chen and Hua (2017) present a setup in which firms and consumers can take precautions. The precaution by the firm influences the gross level of harm in the accident state. The precaution by consumers lowers the level of harm independently of the firm's level of precaution. Inspired by this setting, we assume that the level of expected harm in the risky-product state is equal to $h + D(\vartheta)$, where $h > 0$ is a random variable (as described in Section 2) and $D(v) > 0$ with $D' < 0 < D''$ applying when the level of consumer mitigation costs ϑ is varied. We assume that the firm first chooses product safety and decides about harm mitigation before the consumer assesses the own optimal mitigation. The firm's harm mitigation reduces the total level of expected harm to $(1-\eta)(h+D(\vartheta))$. Accordingly, the socially optimal level of consumer mitigation is described by

$$-(1-\eta)D'(\vartheta_m^*) = 1$$

and

$$-D'(\vartheta_n^*) = 1$$

when the firm does or does not mitigate harm, respectively. This shall define the history-dependent precaution standard for consumers.

When the social planner implements strict liability with a defense of contributory negligence, we assume that the firm is liable for a share γ of both harm and consumer precaution costs when the consumer in question was non-negligent (see also Visscher 2009). In other words, a negligent consumer bears total remaining harm plus consumer precaution costs and a non-negligent consumer bears only share $(1-\gamma)$ thereof. This gives the consumer incentives to obey the standard as

$$h + D(\vartheta_n) + \vartheta_n > h + D(\vartheta_n^*) + \vartheta_n^* \geq (1-\gamma)\left[h + D(\vartheta_n^*) + \vartheta_n^*\right]$$

$$(1-\eta)(h + D(\vartheta_m)) + \vartheta_m > (1-\eta)(h + D(\vartheta_m^*)) + \vartheta_m^* \geq (1-\gamma)\left[(1-\eta)(h + D(\vartheta_m^*)) + \vartheta_m^*\right]$$

for any suboptimal level of consumer care. The firm is then responsible for the minimized sum of consumer mitigation costs and expected harm according to its liability share. The critical harm level for ex-post harm mitigation results as

$$h_M = \min\left\{\overline{h}, \frac{\Omega(q)/q}{\gamma\eta} - \frac{\Delta}{\eta}\right\}$$

where $\Delta = D(\vartheta_n^*) + \vartheta_n^* - (1-\eta)D(\vartheta_m^*) - \vartheta_m^*$. Profits are given by (9) with the expected harm in the event of a risky product $H(h_M)$ being replaced by expected total losses

$$H(h_M) = E[h] + D(\vartheta_n^*) + \vartheta_n^* - \int_{h_M}^{\overline{h}} (\eta h + \Delta)\, dF(h).$$

The remaining analysis parallels our main analysis.

A.2 Compensating consumers as an additional instrument of the policy maker/firm

When mitigating harm implies a transfer of d to each individual consumer, the firm's cost comparison in Stage 2 leads to a critical harm level

$$h_M^d = \min\left\{\overline{h}, \frac{\Omega(q)/q + d}{\gamma\eta}\right\},$$

which implies that, for a given level of output, a higher compensation payment d (which will deter harm mitigation) must be paired with higher liability γ (as this will make mitigating harm attractive for the firm) to maintain the same subgame-perfect mitigation decision by the firm.

Turning to ex-ante profits, we observe that the compensation payment d does not influence profits directly. Comparing the compensation scenario to our baseline analysis, we start from the observation that – for a given level of output – the same cutoff level h_M can be attained by the use of a positive compensation payment paired with a higher level of liability and then investigate the implications for output. Starting at symmetric critical harm levels, a change in output measured by the change in the valuation of the marginal consumer v_M will have a weaker effect on the critical harm level in Stage 2, as

$$\frac{\partial h_M^d}{\partial v_M} = \frac{g(v_M)M}{\eta\gamma q^2}$$

decreases in the liability share γ. Using $d > 0$ paired with a higher γ to induce the same subgame-perfect critical harm level thus induces a smaller distortion in output.

When the firm chooses the compensation payment in Stage 1, it can use d to avoid the commitment problem altogether and implement the ex-ante profit-maximizing critical harm level as its subgame-perfect choice in Stage 2. As argued above, the profit equation does not depend directly on the level of d, but indirectly via h_M^d. Given the level of liability, from (9) the firm's first-order condition for d is

$$\frac{\partial \pi}{\partial d} = -(1-\theta)f(h_M^d)\left[(\eta h_M^d - \tau v_M)q - \Omega(q)\right]\frac{\partial h_M^d}{\partial d} = 0,$$

and is solved by

$$d^M = \gamma \tau v_M - \frac{\Omega(q)(1-\gamma)}{q}.$$

A.3 Product differentiation with regard to harm mitigation

In this section, we concentrate on the scenario with full-market coverage. We first elaborate on the idea that the firm offers a second-product variety without future harm mitigation. We show that having only a subgroup of consumers affected by harm mitigation can separate private and social incentives more strongly when a portion of harm mitigation costs are fixed. Afterwards, we consider the firm's strategic use of harm mitigation thresholds to better price discriminate between different consumer types when the firm can commit to future use of harm mitigation.

To evaluate the firm's incentives with two product varieties, we first sketch the social optimum when harm mitigation is not applied to consumers with a high valuation. Starting from the specification of welfare with one product variety (i.e., SW in (7)), we obtain welfare with two product varieties as

$$\widetilde{SW} = SW + (1-\theta)q_n\left[1 - F(h_M)\right]\left\{\tau E[v|v \geq \hat{v}] + m - \eta E[h|h \geq h_W]\right\}$$

where $q_n = 1 - G(\hat{v})$ and $\hat{v}$ divides the population of consumers into those using the product with harm mitigation (when $v \in [\underline{v}, \hat{v})$) and without it (when $v \in [\hat{v}, \overline{v}]$). For the latter group, the loss in consumption value, variable mitigation costs, and harm reduction are not relevant as harm mitigation is applied only to the product variety with future harm mitigation. Assuming an interior solution, the social optimum is described by

$$\frac{\partial \widetilde{SW}}{\partial \hat{v}} = (1-\theta)g(\hat{v})\left[1-F(h_W)\right]\left\{\eta E[h|h \geq h_M] - \tau\hat{v} - m\right\} = 0 \tag{12}$$

$$\frac{\partial \widetilde{SW}}{\partial h_M} = \frac{\partial SW}{\partial h_W} - (1-\theta)f(h_M)q_n\left\{\tau E[v|v \geq \hat{v}] + m - \eta h_M\right\} = 0 \tag{13}$$

$$\frac{\partial \widetilde{SW}}{\partial \theta} = \frac{\partial SW}{\partial \theta} - \left[1-F(h_M)\right]q_n\left\{\tau E[v|v \geq \hat{v}] + m - \eta E[h|h \geq h_M]\right\} = 0 \tag{14}$$

Using (12) to interpret (13), we have $\tau E[v|v \geq \hat{v}] + m - \eta h_M = \tau(E[v|v \geq \hat{v}] - \hat{v}) + \eta(E[h|h \geq h_M] - h_M) > 0$, implying that the social planner would like to decrease the critical harm level when a second product variety exists. Furthermore, using (12) to interpret (14), we find that $\tau E[v|v \geq \hat{v}] + m - \eta E[h|h \geq h_M] = \tau(E[v|v \geq \hat{v}] - \hat{v}) > 0$, meaning that the social planner's incentives to invest in product safety are smaller when a second product variety exists.

Turning to the firm, we assume that both varieties give right to consumer compensation for any harm incurred to the extent γ.[20] Denoting the price for the product variety with(out) harm mitigation by p^U (p^N), the respective payoffs for an individual with consumption benefits v are:

$$\begin{aligned} V^U =& v\left(1-(1-\theta)\tau\left[1-F(h_M)\right]\right) - (1-\theta)(1-\gamma)H(h_M) - p^U \\ V^N =& v - (1-\theta)(1-\gamma)E[h] - p^N. \end{aligned}$$

Both payoffs increase with v, but V^N increases at a faster rate. The marginal consumer with $v = \hat{v}$ is indifferent between the two product varieties (i.e., $V^N = V^U$). We obtain $p^U = p$ as in (1) and

$$p^N = p + (1-\theta)\int_{h_M}^{\bar{h}} (\tau\hat{v} - (1-\gamma)\eta h)dF(h),$$

which leads to profits

$$\widetilde{\pi} = \pi + (1-\theta)q_n\left[1-F(h_M)\right]\left[\tau\hat{v} - \eta E[h|h \geq h_M]\right]. \tag{15}$$

Considering the firm's mitigation incentives in Stage 2, the critical harm level can be written as

$$h_M = \min\left\{\overline{h}, \frac{\Omega(q_u)/q_u}{\gamma\eta}\right\}$$

[20] Other scenarios may associate the purchase of the no-mitigation variety with forfeiting the right to compensation.

where $q_u = 1 - q_n$ is the number of consumers purchasing the product with harm mitigation. Accordingly, when harm mitigation entails fixed costs and all else is held equal, the firm's willingness to mitigate harm is reduced by the presence of the second product variety because the reduction in expected liability payments pertain only to consumers with $v \in [\underline{v}, \hat{v})$.

Turning to the firm's choice of product safety in Stage 1, we find

$$\frac{\partial \widetilde{\pi}}{\partial \theta} = \frac{\partial \pi}{\partial \theta} - [1 - F(\theta_M)]\, q_n\, [\tau \hat{v} - \eta E[h|h \geq h_M]] = 0.$$

As is clear from (15), the firm offers a second product variety only if the term in brackets is positive. This fact reveals that the firm has weaker incentives to invest in product safety when a second product variety exists.

Next, we highlight that a firm which screens consumers with private information about their valuation may want to distort harm mitigation thresholds in order to enable a more profitable price discrimination. In this section, we concentrate on the scenario with full-market coverage and assume $M = 0$ for simplicity.

The firm offers products characterized by price and harm mitigation threshold. With two differentiated products that may possibly also be distinguished by the associated level of liability, $\gamma^H \neq \gamma^L$, the payoff from buying a product with the high (low) mitigation threshold can be stated as

$$V_H = v\big(1 - (1-\theta)\tau[1 - F(h_H)]\big) - (1-\theta)(1-\gamma^H)H(h_H) - p_H \tag{16}$$

$$V_L = v\big(1 - (1-\theta)\tau[1 - F(h_L)]\big) - (1-\theta)(1-\gamma^L)H(h_L) - p_L \tag{17}$$

Two product variants can be sold only when $h_H \neq h_L$ as otherwise one product is (weakly) dominated by the other product for all consumers. With $h_H < h_L$, the payoff difference $V^L - V^H$ is increasing in v such that high valuation consumers self-select into the product variety with a high harm mitigation threshold. The indifferent consumer is located at v_H so that

$$p_L = v_H(1-\theta)\tau[F(h_L) - F(h_H)] - (1-\theta)[(1-\gamma^L)H(h_L) - (1-\gamma^H)H(h_H)] + p_H \tag{18}$$

With full market coverage, the price for the variety with a low harm mitigation threshold induces indifference of the consumer with the lowest valuation; thus, we obtain

$$p_H = \underline{v}(1 - (1-\theta)\tau[1 - F(h_H)]) - (1-\theta)(1-\gamma^H)H(h_H) \tag{19}$$

leading to

$$p_L = v_H(1-\theta)\tau[F(h_L)-F(h_H)] - (1-\theta)(1-\gamma^L)H(h_L) + \underline{v}(1-(1-\theta)\tau[1-F(h_H)]) \quad (20)$$

The firm's profits are given by

$$\begin{aligned}\widetilde{\pi} =& p_L(1-q_H) + p_H q_H - C(\theta)\\ &-(1-\theta)\big((1-q_H)(\gamma^L H(h_L) + m(1-F(h_L)) + q_H(\gamma^H H(h_H) + m(1-F(h_H))\big)\\ =& q_H(\underline{v} - (1-\theta)(H(h_H) + (1-F(h_H))(m+\tau\underline{v}))\\ &+(1-q_H)(\underline{v} - (1-\theta)(H(h_L) + (1-F(h_L))m + \tau v_H[F(h_L)-F(h_H)] + \tau[1-F(h_H)]\underline{v}))\\ =& \pi + (1-q_H)(1-\theta)(F(h_L)-F(h_H))\big(\tau v_H + m - \eta E[h|h_H \leq h \leq h_L]\big] \quad (21)\end{aligned}$$

where π is as defined in Section 3, where h_H replaces h_M. The firm wants to implement harm mitigation thresholds that maximize ex-ante expected profits, but may be constrained by the fact that harm mitigation thresholds must be subgame-perfect. Now, if the firm can choose liability levels, this is tantamount to determining the threshold values h_J directly, $J = L, H$. We obtain

$$\begin{aligned}\frac{\partial\widetilde{\pi}}{\partial h_H} =& \frac{\partial\pi}{\partial h_H} - (1-q_H)(1-\theta)f(h_H)(\tau v_H + m - \eta h_H) = 0 \quad (22)\\ \frac{\partial\widetilde{\pi}}{\partial h_L} =& (1-q_H)(1-\theta)f(h_L)(\tau v_H + m - \eta h_L) = 0 \quad (23)\end{aligned}$$

where

$$\frac{\partial\pi}{\partial h_H} = (1-\theta)f(h_H)(\tau\underline{v} + m - \eta h_H),$$

clearly implying $\gamma^H > \gamma^L$. For the variety with the higher harm threshold , we find that the threshold is optimally selected for the consumer with a valuation v_H. This is consistent with our main analysis. In contrast, for the variety with the low harm threshold, we find that the firm implements more frequent harm mitigation than is optimal for the marginal consumer. This results from the firm's incentives to produce a stark difference between the two product varieties and is reminiscent of the argument presented by Choi and Spier (2014) about product offerings characterized by their price level and their level of compensation.

A.4 Individual mitigation agreements

Assume that the market is fully covered, that the level of expected harm is observable, and that each consumer chooses whether to permit harm mitigation. In the event harm mitigation is accepted, the consumer may receive a (possibly negative) transfer from the firm such that the firm effectively buys the right to mitigate harm. We allow for the possibility that a consumer who refuses harm mitigation may receive a lower level of compensation, that is, we distinguish between γ and $\tilde{\gamma} = \gamma - \Delta$ where $\Delta \geq 0$ and γ ($\tilde{\gamma}$) applying in the event harm mitigation is accepted (refused).

First, consider the firm's mitigation choice in Stage 2. Suppose that the firm chose to mitigate harm and now determines the transfer $t(h)$ to be paid to consumers who accept harm mitigation. Consumers compare their payoff from accepting harm mitigation,

$$t(h) - \tau v - (1-\gamma)(1-\eta)h,$$

to their payoff from not accepting harm mitigation,

$$-(1-\tilde{\gamma})h.$$

Since the consumers' payoff from accepting harm mitigation decreases with v, harm mitigation will be accepted only by consumers with $v \leq \hat{v}$, where

$$\tau\hat{v}(h) = t(h) + (1-\gamma)\eta h + \Delta h. \tag{24}$$

When the liability regimes punishes consumers for not accepting harm mitigation, that is, when $\Delta > 0$, the requirement for the level of compensation $t(h)$ to achieve a given threshold $\hat{v}$ is relaxed.

The firm chooses the transfer to minimize its expected costs $\kappa(h)$, consisting of the transfer payments to consumers who agree to harm mitigation, mitigation costs, and remaining expected liability costs

$$\min_{t(h)} \kappa(h) = \left[(1-\eta)\gamma h + t(h)\right] q_u + \tilde{\gamma}h(1-q_u) + \Omega(q_u),$$

where $q_u = G(\hat{v})$ is the number of consumers accepting harm mitigation. The optimal transfer payment from the firm's viewpoint solves[21]

$$q_u - \frac{g(\hat{v})}{\tau}\left[\gamma\eta h - t(h) - m - \Delta h\right] = 0. \tag{25}$$

The firm thus does not offer its maximal willingness to pay for the right to implement harm mitigation (i.e., $\tilde{\gamma}h-(1-\eta)\gamma h-m$), because it is a monopsonist in the market for these rights.[22]

[21] The second-order condition is fulfilled when g' is sufficiently small or negative.

[22] Spier (2011) reports a similar distortion regarding the level of the buyback price in the event of a product recall.

It is interesting to note that a variation in the level of liability does not impact the outcome selected by the firm. To see this, use (24) to replace the transfer $t(h)$ in (25) to obtain,

$$\frac{g(\hat{v})}{\tau}\left[\eta h - \tau\hat{v} - m\right] = q_u, \tag{26}$$

implying that the identity of consumers subject to harm mitigation varies with the level of harm but is independent of the level of liability. This results from the fact that a higher level of liability, either γ or $\tilde{\gamma}$, influences the willingness to pay by the firm and the amount that induces the consumer's indifference between accepting harm mitigation and not accepting harm mitigation in exactly the same way.

Knowing the level of the transfer and the number of consumers who would accept harm mitigation, the firm mitigates harm in Stage 2 when the minimized level of costs involving harm mitigation is weakly less than the expected liability payments without harm mitigation, that is, when

$$\kappa^*(h) \leq \gamma h$$

such that the threshold h_M results from

$$\left(\eta + \frac{\Delta}{q_u}\right) h_M = \tau\hat{v}(h_M) + \frac{\Omega(q_u)}{q_u}.$$

Therefore, the critical harm level is also independent of the level of liability when $\Delta = 0$. When $\Delta > 0$ instead, the critical harm level is influenced by the difference in liability levels, not absolute liability levels, such that a stronger liability penalty for consumers who refuse harm mitigation lowers the critical harm level because a positive Δ makes harm mitigation cheaper for the firm as it lowers transfer payments.

Our main analysis highlighted that the level of liability is relevant to the firm's profits only via its influence of the firm's decision-making in Stage 2. When there are individual mitigation agreements, the level of expected harm is observable, and there are no extra incentives from the liability regime (i.e., when $\gamma_1 = \gamma_2$), liability is also irrelevant for the firm's harm mitigation decision in Stage 2 such that the equilibrium allocation is independent of liability.

A.5 Reputation concerns

In our setup, consumers observe product safety investment before making their purchase decision. In contrast, consumers only anticipate the firm's harm mitigation. With reputation concerns, the firm's profit-maximizing harm mitigation choice must reflect potential repercussions on the firm's reputation and, thus, future profits.

Assume full-market coverage, observable expected harm, an infinite number of periods, and that the firm discounts future payoffs using a discount factor equal to $\delta \in (0,1)$. The firm's ex-ante profits are maximized by committing to the critical harm level h_π. We now consider that consumers play a grim-trigger strategy such that they start off cooperating (i.e., they anticipate h_π as threshold value and exhibit the according willingness to pay) in the first period and switch to a demand function that builds on the anticipation of $h_M(\gamma)$ forever after the firm has deviated from the threshold h_π once.

In any given period, the firm chooses whether to mitigate harm in Stage 2 when the risky-product state materializes. Consumers purchased the product believing that the firm will decide on ex-post remedies according to h_π. In contrast, the current-period profits of the firm would be maximized by the choice of $h_M(\gamma)$, which may either exceed or fall short of the threshold level that maximizes the firm's ex-ante profits. It holds that $h_M - h_\pi > \ (<)\ 0$ when $\gamma < \ (>)\ \gamma_\pi$. The firm's deviating from consumers' beliefs will be noticed as such by consumers only when the harm mitigation choice according to h_π contrasts with the one according to $h_M(\gamma)$. For $\gamma < \gamma_\pi$, this occurs when $h \in [h_\pi, h_M(\gamma))$. In this circumstance, the firm deviates from beliefs when it does not mitigate harm. When instead $h > h_M(\gamma)$ ($h < h_\pi$) the firm would (not) use ex-post harm mitigation according to both threshold levels. For $\gamma > \gamma_\pi$ the firm may deviate when $h \in (h_M(\gamma), h_\pi]$ by mitigating harm in order to save on liability costs, whereas decisions according to both threshold levels are aligned for $h < h_M(\gamma)$ or $h > h_\pi$. Below, we briefly outline the two cases, that is, $\gamma < \gamma_\pi$ and $\gamma > \gamma_\pi$. Recall that, for $\gamma = \gamma_\pi$, the firm has no incentive to commit to any other harm threshold since $h_\pi = h_M(\gamma_\pi)$.

We denote the firm's maximal ex-ante profit by π_{max} and the firm's profit as resulting in the main analysis as $\pi(\gamma)$ (note that $\pi(\gamma_\pi) = \pi_{max}$). When $\gamma < \gamma_\pi$ and $h \in [h_\pi, h_M(\gamma))$, the firm resists the temptation stemming from short-term profit maximization and mitigates harm when

$$\begin{aligned}
&-\Omega - \gamma(1-\eta)h + \frac{\delta}{1-\delta}\pi_{max} > -\gamma h + \frac{\delta}{1-\delta}\pi(\gamma) \\
&\Omega - \eta\gamma h < \frac{\delta}{1-\delta}[\pi_{max} - \pi(\gamma)] \\
&\eta\gamma(h_M(\gamma) - h) < \frac{\delta}{1-\delta}[\pi_{max} - \pi(\gamma)]. \qquad (27)
\end{aligned}$$

The left-hand side of the last inequality is the increase in current profits that results from abstaining from harm mitigation. The firm mitigates harm if this gain is lower than the annuity of the loss in future profits. The gain from deviating is decreasing in actual harm h. The firm will not deviate even when $h \to h_\pi$ as long as δ is sufficiently large, that is, as long as the firm sufficiently values the future. Both the left-hand and the right-hand side of the inequality (27) decrease in γ and tend to zero for $\gamma \to \gamma_\pi$ (since $\pi(\gamma) \to \pi_{max}$ and $h_M(\gamma) \to h_\pi$ for $\gamma \to \gamma_\pi$), implying that it is not possible at a general level to determine whether the reputation mechanism becomes more or less strong when the level of liability is varied. However, inequality (27) clearly indicates that the reputation mechanism can serve as a commitment device (for δ sufficiently large).

When $\gamma > \gamma_\pi$ and $h \in [h_M(\gamma), h_\pi)$, the monopolist sticks to consumers' beliefs, that is, abstains from mitigating harm only when

$$\begin{aligned} -\Omega - \gamma(1-\eta)h + \frac{\delta}{1-\delta}\pi(\gamma) &< -\gamma h + \frac{\delta}{1-\delta}\pi_{max} \\ \eta\gamma(h - h_M(\gamma)) &< \frac{\delta}{1-\delta}[\pi_{max} - \pi(\gamma)], \end{aligned} \tag{28}$$

where the left-hand side increases with h, implying that the firm will never deviate from consumers' beliefs if inequality (28) holds for $h \to h_\pi$. As before, the inequality exemplifies that the loss in the annuity of future profits induces the firm to forfeit a possible short-term gain from reduced liability costs if the firm values the future sufficiently (i.e. δ is high enough).

A.6 Comparative static analysis for the first-order condition (10)

Assume a given level for product safety, $\theta = \bar{\theta}$. The change in output following an increase in the firm's liability share results from

$$\frac{\partial q}{\partial \gamma} = -g(v_M)\frac{\partial v_M}{\partial \gamma} = g(v_M)\frac{\frac{\partial^2 \pi}{\partial v_M \partial \gamma}}{\frac{\partial^2 \pi}{\partial v_M^2}}.$$

For a profit maximum $\frac{\partial^2 \pi}{\partial v_M^2} < 0$. From (10) and starting from $h_M < \overline{h}$ the sign of the change in output is determined by

$$
\begin{aligned}
-\frac{\partial^2 \pi}{\partial v_M \partial \gamma} = & - q(1-\bar{\theta}) f(h_M) \frac{\partial h_M}{\partial \gamma} \tau \\
& - g(v_M)(1-\bar{\theta}) f(h_M) \frac{\partial h_M}{\partial \gamma} \left[\eta h_M - \tau v_M - \Omega'(q)\right] \\
& + q(1-\bar{\theta}) f(h_M) g(v_M) \eta \frac{\partial h_M}{\partial \gamma} \frac{\partial h_M}{\partial q} \\
& - q(1-\bar{\theta}) g(v_M) \left[\eta h_M - \tau v_M - \Omega(q)/q\right] \frac{\partial h_M}{\partial q} \left(f'(h_M) \frac{\partial h_M}{\partial \gamma} - \frac{f(h_M)}{\gamma} \right).
\end{aligned}
$$

The first line is positive and relates to the fact that – due to the direct effect of more likely harm mitigation – the price increase made possible by a reduction in output decreases. The second line describes the effect how the higher likelihood of harm mitigation affects the profit margin per consumer which depends on how the subgame-perfect harm mitigation threshold relates to variable harm mitigation costs. The third and fourth line display how more likely harm mitigation interacts with the firm's use of output to influence its subgame-perfect harm mitigation choice. The third line displays the change in marginal profits due to the commitment effect from a change in output. It is positive due to the now lower expected costs of harm due to more harm mitigation. The fourth line measures the effect on profits stemming from the fact that the change in the firm's liability level alters how effective an increase in output is in affecting the subgame-perfect harm mitigation choice. Whether the latter effect is positive or negative depends on how the alignment of the firm's subgame-perfect mitigation choice with the harm mitigation choice maximizing ex-ante profits (which determines the sign of the term in brackets).

A.7 Comparative static analysis for the first-order condition (11)

For an increase in output, from condition (11), we obtain

$$
\frac{\partial \theta_M}{\partial q} = -\frac{\frac{\partial^2 \pi}{\partial \theta \partial q}}{\frac{\partial^2 \pi}{\partial \theta^2}}.
$$

For the profit-maximum, $\frac{\partial^2 \pi}{\partial \theta^2} < 0$, and the sign for the change in safety is determined by

$$\begin{aligned}\frac{\partial^2 \pi}{\partial \theta \partial q} =& - k'(\theta) \\ &+ H(h_M) + [1 - F(h_M)] \left(\tau v_M + \frac{\Omega(q)}{q} \right) \\ &+ q \frac{\partial h_M}{\partial q} f(h_M) \left\{ \eta h_M - \tau v_M - \frac{\Omega(q)}{q} \right\} \\ &+ q \left[1 - F(h_M)\right] \left(\tau \frac{\partial v_M}{\partial q} - \frac{M}{q^2} \right)\end{aligned}$$

The first line is the direct effect of higher output on marginal product safety costs. The second and third line depict the indirect effect stemming from the change in the firm's subgame-perfect harm mitigation choice resulting from higher output. The sign of the second line depends on whether the increase in output brings subgame-perfect harm mitigation closer to or further away from the harm mitigation choice maximizing ex-ante profits. The fourth line describes how the gain from affecting subgame-perfect harm mitigation varies with output.

For $K(\theta) = M = 0$ we have $\frac{\partial h_M}{\partial q} = 0$ and the third line is equal to zero. The terms in the first two lines cancel out due to (11) implying $k'(\theta) = H(h_M) + [1 - F(h_M)] \left(\tau v_M + \frac{\Omega(q)}{q} \right)$. The only remaining effect is the lower valuation by the marginal consumer in the fourth line, making investments in product safety less profitable.

For $K(\theta) > 0$, from condition (11) $k'(\theta) < H(h_M) + [1 - F(h_M)] \left(\tau v_M + \frac{\Omega(q)}{q} \right)$ such that the sum of the terms in the first line is positive – *ceteris paribus* – arguing for an increase in product safety due to scale effects.

For $M > 0$, another negative term is observed in the fourth line implying a further reduction in the benefits from higher product safety. In addition, $\frac{\partial h_M}{\partial q} < 0$ such that line three is negative (positive) for harm mitigation becoming more (less) aligned with the ex-ante profit maximization.

A.8 Numerical Simulations for Less Than Full Market Coverage

Table 2: Numerical Simulations for Endogenous Output Scenario (Values Rounded to 0.005)

Nr.	$(\mu;\tau;c;k;K;m;M;z_h;z_v)$	γ_n	γ^*	γ_W	γ_π	γ^*_{EXO}	$\theta(\gamma)$
(1)	$(0.9;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.175	0.21	0.25	0.205	dec.-inc.
(2)	$(0.9;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;1)$	0.155	0.2	0.205	0.235	0.205	dec.-inc.
(3)	$(0.9;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0)$	0.15	0.165	0.2	0.25	0.195	dec.-inc.
(4)	$(0.9;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{30};0.5;0.5)$	0.12	0.19	0.21	0.25	0.205	dec.-inc.
(5)	$(0.9;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{30};0;0.5)$	0.08	0.2	0.21	0.25	0.205	dec.-inc.
(6)	$(0.9;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.185	0.195	0.225	0.255	0.225	dec.-inc.
(7)	$(0.8;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.18	0.185	0.21	0.25	0.205	inc.-dec.-inc.
(8)	$(0.9;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.3	0.345	0.4	0.34	dec.-inc.
(9)	$(0.9;0.1;1;0.1;0.1;0;\frac{1}{15};1;0.5)$	0.17	0.18	0.22	0.265	0.22	dec.-inc.
(10)	$(0.9;0.1;1;0.1;0.1;\frac{1}{15};0;1;0.5)$	0.145	0.23	0.195	0.23	0.19	dec.-inc.
(11)	$(0.9;0.1;1;0.1;0.1;\frac{1}{15};0;1;1)$	0.145	0.21	0.195	0.22	0.195	dec.-inc.
(12)	$(0.9;0.1;1;0;0.2;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.165	0.205	0.25	0.205	dec.-inc.
(13)	$(0.9;0.1;1;0.2;0;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.205	0.21	0.25	0.205	dec.-inc.
(14)	$(0.9;0.1;1;0;0.2;\frac{1}{15};0;1;0.5)$	0.145	0.235	0.195	0.23	0.19	dec.-inc.
(15)	$(0.8;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.21	0.215	0.225	0.255	0.225	inc.-dec.-inc.
(16)	$(0.9;0.05;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.185	0.285	0.365	0.405	0.365	dec.-inc.
(17)	$(0.9;0.1;1.5;0.1;0.1;\frac{1}{15};0;1;0.5)$	0.145	0.21	0.185	0.21	0.185	dec.-inc.
(18)	$(0.9;0.1;1.5;0.1;0.1;0;\frac{1}{15};1;0.5)$	0.225	0.235	0.26	0.295	0.265	inc.-dec.-inc.
(19)	$(0.9;0.1;1.5;0.2;0;\frac{1}{30};\frac{1}{30};1;0.5)$	0.19	0.21	0.23	0.26	0.225	dec.-inc.
(20)	$(0.9;0.1;1.5;0;0.2;\frac{1}{30};\frac{1}{30};1;0.5)$	0.185	0.19	0.225	0.255	0.225	inc.-dec.-inc.
(21)	$(0.9;0.1;1.5;0;0.2;\frac{1}{30};\frac{1}{30};0.5;0.5)$	0.14	0.18	0.225	0.255	0.225	inc.-dec.-inc.
(22)	$(0.9;0.1;1.5;0;0.2;\frac{1}{30};\frac{1}{30};0;0.5)$	0.09	0.2	0.225	0.255	0.225	inc.-dec.-inc.
(23)	$(0.9;0.1;1.5;0;0.2;\frac{1}{30};\frac{1}{30};1;1)$	0.165	0.185	0.215	0.235	0.215	inc.-dec.-inc.
(24)	$(0.9;0.1;1.5;0;0.2;\frac{1}{30};\frac{1}{30};1;0)$	0.185	0.195	0.225	0.265	0.225	inc.-dec.-inc.
(25)	$(0.9;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0)$	0.19	0.195	0.225	0.265	0.225	inc.-dec.-inc.
(26)	$(0.9;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;1)$	0.165	0.195	0.215	0.235	0.215	dec.-inc.
(27)	$(0.9;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};0;1)$	0.08	0.205	0.215	0.235	0.215	dec.-inc.
(28)	$(0.8;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.18	0.295	0.345	0.4	0.34	dec.-inc.
(29)	$(0.8;0.05;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.21	0.285	0.365	0.41	0.37	inc.-dec.-inc.
(30)	$(0.8;0.05;1;0.1;0.1;\frac{1}{15};0;1;0.5)$	0.165	0.375	0.325	0.375	0.32	dec.-inc.
(31)	$(0.8;0.05;1;0.1;0.1;0;\frac{1}{15};1;0.5)$	0.19	0.23	0.355	0.42	0.36	dec.-inc.

Nr.	Parameter Values $(\mu;\tau;c;k;K;m;M;z_h;z_v)$	γ_n	γ^*	γ_W	γ_π	γ^*_{EXO}	$\theta(\gamma)$
(32)	$(0.8;0.05;1;0.2;0;\frac{1}{30};\frac{1}{30};1;0.5)$	0.18	0.33	0.345	0.4	0.34	dec.-inc.
(33)	$(0.8;0.05;1;0;0.2;\frac{1}{30};\frac{1}{30};1;0.5)$	0.175	0.245	0.34	0.395	0.34	dec.-inc.
(34)	$(0.8;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};0.5;0.5)$	0.135	0.325	0.345	0.4	0.34	dec.-inc.
(35)	$(0.8;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};0;0.5)$	0.09	0.335	0.345	0.4	0.34	dec.-inc.
(36)	$(0.8;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;1)$	0.175	0.335	0.345	0.38	0.34	dec.-inc.
(37)	$(0.8;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0)$	0.17	0.26	0.335	0.4	0.33	dec.-inc.
(38)	$(0.9;0.1;1;0.1;0.1;\frac{1}{15};0;1;0.5)$	0.235	0.255	0.275	0.325	0.275	dec.-inc.
(39)	$(0.9;0.1;1;0.1;0.1;\frac{1}{30};\frac{1}{15};1;0.5)$	0.25	0.255	0.29	0.34	0.285	dec.-inc.
(40)	$(0.9;0.1;1;0.2;0.1;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.19	0.21	0.25	0.21	dec.-inc.
(41)	$(0.9;0.1;1;0.1;0.2;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.18	0.21	0.25	0.21	inc.-dec.-inc.
(42)	$(0.8;0.1;1.5;0.1;0.1;\frac{1}{15};0;1;0.5)$	0.165	0.21	0.185	0.21	0.185	dec.-inc.
(43)	$(0.8;0.1;1.5;0.1;0.1;0;\frac{1}{15};1;0.5)$	0.255	0.265	0.26	0.295	0.265	inc.-dec.-inc.
(44)	$(0.8;0.1;1.5;0.2;0;\frac{1}{30};\frac{1}{30};1;0.5)$	0.215	0.22	0.23	0.26	0.23	dec.-inc.
(45)	$(0.8;0.1;1.5;0;0.2;\frac{1}{30};\frac{1}{30};1;0.5)$	0.21	0.215	0.225	0.255	0.225	inc.-dec.-inc.
(46)	$(0.8;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};0;0.5)$	0.105	0.205	0.225	0.255	0.225	inc.-dec.-inc.
(47)	$(0.8;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;1)$	0.185	0.19	0.215	0.235	0.215	inc.-dec.-inc.
(48)	$(0.8;0.1;1.5;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0)$	0.215	0.22	0.225	0.265	0.23	inc.-dec.-inc.
(49)	$(0.9;0.05;1;0.1;0.1;\frac{1}{15};0;1;0.5)$	0.145	0.375	0.325	0.375	0.32	dec.-inc.
(50)	$(0.9;0.05;1;0.1;0.1;0;\frac{1}{15};1;0.5)$	0.17	0.22	0.355	0.415	0.36	dec.-inc.
(51)	$(0.9;0.05;1;0.2;0;\frac{1}{30};\frac{1}{30};1;0.5)$	0.16	0.33	0.345	0.4	0.34	dec.-inc.
(52)	$(0.9;0.05;1;0;0.2;\frac{1}{30};\frac{1}{30};1;0.5)$	0.155	0.27	0.34	0.395	0.34	dec.-inc.
(53)	$(0.9;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};0;0.5)$	0.08	0.335	0.345	0.4	0.34	dec.-inc.
(54)	$(0.9;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;1)$	0.155	0.335	0.345	0.38	0.34	dec.-inc.
(55)	$(0.9;0.05;1;0.1;0.1;\frac{1}{30};\frac{1}{30};1;0)$	0.15	0.275	0.335	0.4	0.33	dec.-inc.

Notes: The column γ^*_{EXO} reports the socially optimal level of liability for the scenario in which the level of output attained at γ^* is an *exogenous* component of the framework. The comparison of γ^* and γ^*_{EXO} describes the influence of output being endogenous. The last column describes profit-maximizing product safety investments as a function of liability, where *dec.-inc.* means that – for liability levels surpassing γ_n – the product safety investment level first decreases and later increases with the level of liability (i.e., that product safety is a u-shaped function of liability). For *inc.-dec.-inc.* the investment level first increases after liability surpasses γ_n before describing a u-shape.

Figure 1: Critical harm levels h_M (bold curve) and h_W (dashed curve) (first panel), the level of output q (second panel), and product safety θ_M (third panel) as a function of liability

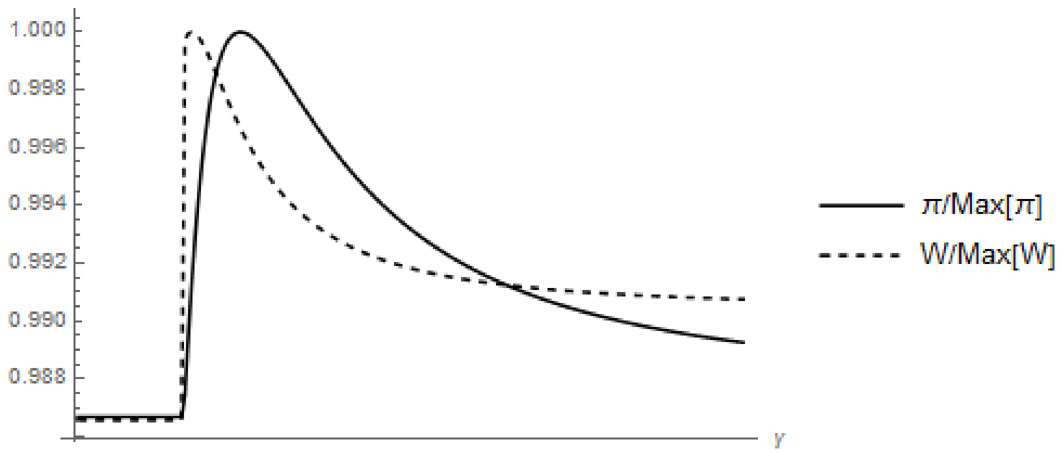

Figure 2: Ex-ante expected profits (bold curve) and social welfare (dashed curve) relative to their respective maximum values