Equilibrium and Welfare in a Model of Torts with Industry Reputation Effects[*]

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Abstract

We study the problem of torts in a framework where a firm's accident adversely impacts all firms in the industry because of the presence of industry reputation effects. Industry reputation effects lead to interdependence among firms and give rise to strategic firm behavior. We characterize the industry equilibrium and the socially optimal industry configuration in such a setting. We then elucidate how the presence of industry reputation effects and the introduction of a liability regime in the form of a strict liability rule determine whether industry equilibrium is aligned or misaligned with the socially optimal industry configuration. Our results show that both the impact of industry reputation effects and the impact of the strict liability rule are in general contingent on the specifics of the tort problem at hand. In particular, we find that the presence of industry reputation effects can substitute for a suboptimal liability regime and that, in the presence of industry reputation effects, the introduction of the strict liability rule may be detrimental by steering the industry equilibrium away from the socially optimal industry configuration.

Keywords: Industry reputation effects, torts, industry equilibrium, social welfare, strict liability

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1. Introduction

When a firm's accident casts a negative light on rival firms, firms in the industry find themselves "tarred by the same brush" (King et al. 2002: 393). Examples abound: "the Union Carbide accident in Bhopal, India, damaged public perception of the entire chemical industry….[t]he Exxon Valdez oil spill affected all members of the petroleum industry….[t]he Three Miles incident was caused by the missteps of a single firm at a single facility, but the reputation of the entire power industry was harmed" (ibid.: 394). Similarly, the outbreak of E. coli in the U.S. caused by a single farm led to a profound and lasting drop in retail sales in the entire industry of bagged spinach (Pouliot and Sumner 2010) and the 2009 announcement by the Federal Drug Administration that a sample of pistachios delivered by one particular firm had tested positive for salmonella "came at a high price for the [whole] pistachio industry" (ibid.: 2).

That one firm's mistake may "soil the reputation of an entire industry" (Barnett 2008: 7) has been well acknowledged in the recent literature on organizational behavior and management (see, e.g., King et al. 2002; Barnett 2007; Barnett and King 2008; Yu et al. 2008; Barnett and Hoffman 2008).[1] However, the possibility that firm behavior may be influenced by industry reputation effects has thus far not been explored in the analyses of the problem of torts.[2]

In this paper, we develop a model of torts to study firm behavior in the presence of industry reputation effects. We aim to shed light on the following questions: How does the presence of industry reputation effects shape firms' decision to invest in precaution? What is the socially optimal industry configuration in the presence of industry reputation effects? How does the equilibrium industry configuration, resulting from non-cooperative decision-making of firms,

[1] See also Special Issue: Beyond Corporate Reputation: Managing Reputational Interdependence in *Corporate Reputation Review*, Volume 11, Issue 1 (Spring 2008).
[2] The standard law-and-economics model of torts is developed, for example, in Shavell (2004, 2007), Cooter and Ulen (2012) and Miceli (2008).

in the presence of industry reputation effects compare with the socially optimal industry configuration? How do industry reputation effects and a liability regime determine the extent of alignment (or misalignment) between the equilibrium and socially optimal industry configuration?

When firms in the industry share a common reputation, a firm's investment in precaution not only reduces the firm's likelihood of an accident, and thus the firm's expected damage compensation costs, but also decreases the expected costs from diminished industry reputation for every firm in the industry. In the presence of industry reputation effects, firms' fates are, therefore, "intertwined" (Barnett and King 2008: 1152) and a firm's decision to invest in precaution is—unlike in the conventional model of torts (see, e.g., Shavell 2004: Sec.II, 2007; Cooter and Ulen 2012: Ch.6,7; Miceli 2008: Ch.2,3)—inherently strategic.[3]

Drawing on the above insight, we characterize the Nash equilibrium of a static game with complete information in which identical firms comprising the industry are choosing between investing and not investing in precaution in the presence of industry reputation effects. We find that when industry reputation effects are either very strong or very weak relative to the magnitude of firm's cost of precaution net of expected liability damages, firms in the equilibrium exhibit uniformity in behavior. Specifically, when industry reputation effects are very weak, the equilibrium industry configuration entails no firm in the industry investing in precaution. In contrast, when industry reputation effects are very strong, the equilibrium industry configuration involves all firms investing in precaution.

An equilibrium in which ex ante homogeneous firms display ex post heterogeneous behavior is possible as well. With a firm's ex-post costs due to diminished industry reputation

[3] For a model of strategic firm interaction examining optimal products liability, and emphasizing consumer misperceptions of risk and market structure, see Polinsky and Rogerson (1983).

increasing at an increasing rate with the number of accidents in the industry, the equilibrium may feature a strictly positive number of firms that invest in precaution and the remainder of the industry not investing in precaution. This equilibrium configuration arises when a firm's cost of precaution net of expected liability is positive and of intermediate magnitude.

We next characterize the socially optimal industry configuration. Since the firms' expected costs from diminished industry reputation increase with the number of firms that do not invest in precaution, the socially optimal industry configuration always entails all firms investing in precaution when investing in precaution would have been socially desirable in the absence of industry reputation effects. However, when investing in precaution would not have been socially desirable in the absence of industry reputation effects, and when firms' expected losses from diminished industry reputation give rise to net social costs, the socially optimal industry configuration may entail a strictly positive number of firms not investing in precaution.

We then contrast the equilibrium industry configuration with the socially optimal industry configuration for a given tort problem under consideration. Specifically, we highlight how the two institutional mechanisms shaping firms' incentives—liability regime in the form of a strict liability rule and industry reputation effects—influence whether the equilibrium industry configuration is aligned or misaligned with the socially optimal industry configuration.

We find that, in certain scenarios, the presence of industry reputation effects can substitute for a suboptimal liability regime—more precisely, the existence of a common industry reputation can steer the equilibrium industry configuration toward the socially optimal industry configuration when in the absence of a common industry reputation the industry equilibrium would have been socially suboptimal. In some other scenarios, however, the presence of industry reputation effects can have the exact opposite effect—it pushes the industry equilibrium toward a socially suboptimal industry configuration when in the absence of a common industry reputation the industry equilibrium would have coincided with the socially optimal industry configuration.

A qualitatively similar pattern of conclusions emerges when we examine the impact of the introduction of a strict liability rule in the presence of industry reputation effects. That is, under some conditions, the introduction of a strict liability rule can align the industry equilibrium with the socially optimal industry configuration when the two would have been misaligned in the absence of a liability regime. In some other scenarios, however, the introduction of a strict liability rule may steer the industry equilibrium away from the socially optimal industry configuration.

In sum, our findings suggest that the impact of industry reputation effects crucially depends on the specifics of the tort problem at hand, and that the introduction of a liability regime in the presence of industry reputation effects is not necessarily beneficial.

This paper contributes to a recently revived literature exploring whether market forces may act as a disciplining mechanism ensuring socially desirable investment in precaution, and thus complement or even substitute for tort law and regulation (Polinsky and Shavell 2010, Rubin 2011, Ganuza et al. 2011). Within this literature, Ganuza et al. (2011) study analytically how product liability and relational contracting, leading to firm-level reputation effects, interact in influencing a firm's incentives to exert care. We, in contrast, study firm behavior under a strict liability rule in the presence of *industry* reputation effects. Unlike Ganuza et al. (2011), we analyze how industry reputation effects and the strict liability rule interact in determining the extent of alignment between the industry equilibrium and socially optimal industry structure.

At a more general level, the importance of collective reputations has been emphasized by Tirole (1996). Tirole has shown that the phenomenon of collective reputation emerges when individual behaviors are imperfectly observed. Building on Tirole's insight, the industrial organization literature has studied the incentives of firms to provide quality in a setup where consumers observe only the average quality of the good produced in the industry (Winfree and McCluskey 2005, Carriquiry and Babcock 2007, Fleckinger 2007, Rouviére and Saubeyran 2011, McQuade et al. 2010). We, in contrast, address the problem of torts and examine how industry reputation effects shape firms' incentives to invest in precaution reducing the likelihood of accidents.

Pouliot and Sumner (2010) examine how firms' incentives to provide food safety vary with the extent to which the origin of a failed product can be traced back to the producer. We study an environment where there is either no traceability (see, e.g., Winfree and McCluskey 2005; Fleckinger 2007; McQuade et al. 2010; Rouvière and Saubeyran 2011), or where industry reputation effects arise even when the culprit firm is known (see, e.g., Barnett 2007; Barnett and King 2008; Yu et al. 2008). Unlike Pouliot and Sumner (2010), we recognize the strategic nature of firms' choices to invest in precaution, characterize both the equilibrium and socially optimal industry configuration, as well as study how the interaction between industry reputation effects and a liability regime determines the extent of alignment between the equilibrium and socially optimal industry configuration.

The rest of the paper is organized as follows. Section 2 develops the model's setup. Sections 3 and 4 respectively characterize the industry equilibrium and socially optimal industry configuration in the presence of industry reputation effects. Section 5 examines how the relationship between the equilibrium and socially optimal industry configuration varies depending on the presence or absence of industry reputation effects and a liability regime in the form of the strict liability rule. Section 6 concludes.

2. The Model

Consider an industry comprised of n identical firms. Each firm conducts an activity which may lead to an accident causing social harm (for example, pollution affecting third parties or injuries to a firm's customers in the case of defect products). The probability that a firm causes an accident equals $P \in (0,1)$. The social harm if an accident takes place equals $H>0$. The firm, however, can eliminate the risk of an accident by investing in precaution. Let the associated cost of precaution be $C>0$.

Firms' incentives to invest in precaution are shaped, first, by tort law. Under the strict liability rule, a firm is liable for payment of damage compensation whenever an accident occurs. Let a firm's expected liability costs in the case of an accident equal L. We assume that $L<H$: firms may be judgment proof because of liability caps or insolvency (Shavell 1984a, 1986), lawsuits need not take place even though harm has been done (DeGeest and Dari-Mattiacci 2007, Shavell 1984b), and given the inherent incompleteness of law (Pistor and Xu 2003), a firm may escape liability even if taken to court.[4]

In addition, a firm's choice on whether to invest in precaution is influenced by actions taken by other firms in the industry because of industry-wide reputation effects. Industry reputation effects arise when one firm's actions influence the observers' perceptions of the industry as a whole.[5] In the presence of a common industry-wide reputation, a firm's accident reflects negatively not only on the firm causing the accident, but on the entire industry (see, e.g., King et al. 2002; Barnett 2007; Barnett and King 2008; Pouliot and Sumner 2010). The presence

[4] L should be interpreted as the product of (i) the probability that the firm is taken to court and loses its case in the case of an accident and (ii) the amount of damage compensation the firm has to pay. In the case when an accident in the industry can be perfectly traced back to the firm causing it, L in addition also entails pecuniary losses due to diminished *firm*-specific reputation.

[5] We do not model how a common, industry-wide reputation is formed in the first place. (Tirole (1996) studies the emergence of collective reputation.) Instead, we take the existence of industry-wide reputation as given and examine its repercussions.

of industry reputation effects, therefore, implies that firms in the industry are, unlike in the standard models of torts, *interdependent*.

We model industry reputation effects as follows. If $k<n$ firms in the industry invest in precaution, the remaining $m \equiv n-k$ firms are prone to causing an accident. Hence, the probability that exactly $j \in \{0,1,\ldots,m\}$ accidents take place in the industry is

$$(1) \qquad \binom{m}{j} P^{j}(1-P)^{m-j}.$$

Expression (1) is the probability density function of a random variable following a binomial distribution characterized by $m \equiv n-k$ independent (Bernoulli) trials with 'success probability' P (see, e.g., Mood et al. 1974).

Let $\rho(j)$ be the ex post loss incurred by each firm in the industry due to diminished industry reputation if exactly j accidents occur in the industry. When an accident takes place and firms in the industry are bound by a common reputation, all firms suffer a loss because "consumers may suddenly boycott all products or services of this type, communities may refuse to allow production facilities in their neighborhoods, [and] employees may be unwilling to work in these firms" (Barnett 2007: 6-7). To ensure tractability, we parameterize $\rho(j)$ so that the ex post loss to each firm in the industry due to diminished industry reputation is quadratic in the number of accidents $j \in \{0,1,\ldots,m\}$:

$$(2) \qquad \rho(j) = 0.5\alpha \cdot j^{2} + \beta \cdot j.$$

Observers' perceptions of an industry are based on expectations and norms, which tend to be stable and resistant to change (Barnett 2007: 7; Barnett and King 2008). However, "[t]hese perceptions can change 'suddenly and unpredictably'…as significant events influence taken-for-granted assumptions and create new metaphors about the industry. These new metaphors influence the interpretation of future events, and they can cause even minor events to draw attention and raise the threat of greater sanctions across the industry" (Barnett and King 2008: 1153). Indeed, evidence from many industries "validates the perspective that a major crisis can alter perceptions of an industry and, as a result, future problems within the industry carry the risk of more severe industrywide harm" (ibid.). We, therefore, model the loss incurred by each firm in the industry due to diminished industry reputation as increasing with the number of accidents j, plausibly at an increasing rate: $\alpha>0$ and $\beta>0$.[6]

The magnitude of parameters α and β captures the strength of industry reputation effects. The strength of industry reputation effects depends on the ability of the outside observers to sanction the industry, which in turn varies with attributes of the stakeholders and properties of the industry under consideration. Ceteris paribus, "[m]ore numerous, distant, and heterogeneous stakeholders are less likely to coordinate their influence, and thus less likely to build into a sufficiently powerful…force to sway firm actions" (King et al. 2002: 397). Similarly, "[c]oncentrated industries may be able to use their market power to offset stakeholder action", and "industries in the early stages of the value chain may be less vulnerable to boycotts or other manifestations of stakeholder pressure, as their products and services are less visible and thus less subject to scrutiny" (ibid.: 398).

When $m\equiv n-k$ firms in the industry choose not to invest in precaution, the expected loss incurred by each firm in the industry due to diminished industry reputation therefore equals

(3) $$R(m)=\sum_{j=0}^{m}\binom{m}{j}P^{j}(1-P)^{m-j}\rho(j),$$

[6] With $\alpha>0$ and $\beta>0$, $\Delta_\rho(j)\equiv\rho(j+1)-\rho(j)=0.5\alpha(2j+1)+\beta>0$ and $\Delta_\rho^2\equiv\Delta_\rho(j+1)-\Delta_\rho(j)=\alpha>0$. The model remains tractable, and the qualitative nature of our results in Section 5 remains largely unchanged, if $\alpha=0$. In contrast, the assumption that $\alpha<0$ is empirically unjustifiable since it implies that a firm's ex-post loss due to diminished industry reputation eventually *de*creases with the number of accidents in the industry.

where $\rho(j)$ is given in (2). Taking into account the properties of the binomial distribution, (3) can be written as (see Appendix):

(4) $R(m) = m^2 0.5\alpha P^2 + m[0.5\alpha P(1-P)+\beta P]$.

The following result summarizes the key properties of $R(m)$. (We relegate proofs of all results to the Appendix.)

Lemma 1: *Let* $\Delta_R(m)\equiv R(m+1)-R(m)$ *and* $\Delta^2{}_R(m)\equiv\Delta_R(m+1)-\Delta_R(m)$. *Then,*

(i) $\Delta_R(m)=\alpha P^2 m+0.5\alpha P+\beta P>0$ *for all* $m\in\{0,1,\ldots,n\}$,

(ii) $\Delta^2{}_R(m)=\alpha P^2>0$ *for all* $m\in\{0,1,\ldots,n\}$,

(iii) $\Delta_R(m)$ *is strictly increasing in* α *and* β.

With fewer firms investing in precaution, the expected number of accidents in the industry increases. Given that the ex post loss incurred by each firm in the industry due to diminished industry reputation increases with the number of accidents at an increasing rate, the expected loss to a firm because of diminished industry reputation increases at an increasing rate with the number of firms in the industry that do not invest in precaution (Lemma 1, parts (i) and (ii)). Moreover, the rate of change of a firm's expected loss because of diminished industry reputation with respect to the number of firms not taking precaution increases with the strength of industry reputation effects as captured by α and β (Lemma 1, part (iii)).

3. Industry Equilibrium

At the firm level, an investment in precaution is costly, but it eliminates the risk of an accident and thus the need to pay any compensation damages. At the same time, investing in precaution reduces the firm's expected costs due to industry reputation effects from $R(m+1)$ to $R(m)$ when $k=n-(m+1)$ other firms in the industry also invest in precaution. In contrast, not investing in precaution saves the firm the cost of precaution, but exposes the firm to the risk of causing an accident and of having to pay compensation damages. In addition, the decision to not invest in precaution increases the firm's expected costs due to industry reputation effects from $R(m)$ to $R(m+1)$ when $m=n-k$ other firms in the industry also do not invest in precaution.

In an environment with industry reputation effects, a firm's payoff from a given action therefore depends on the actions taken by other firms in the industry. Unlike in the traditional analyses of the problem of torts (see, e.g., Shavell 2004, 2007; Cooter and Ulen 2012; Miceli 2008), in our framework, firms in the industry are interdependent and each firm's decision on whether to invest in precaution is, therefore, inherently strategic (in game-theoretic sense).

We explore when a specific industry configuration, summarized by the number of firms that do not invest in precaution $m \equiv n-k$, is a strict Nash equilibrium of a static game with complete information in which firms simultaneously and independently choose whether to invest in precaution.

Industry configuration such that all firms in the industry are investing in precaution ($m=0$) is a strict Nash equilibrium if no firm currently investing in precaution has an incentive to instead not invest in precaution, that is, if

(5) $C+R(0)<P\cdot L+R(1)$.

The left-hand side of the inequality (5) is a firm's expected cost if the firm invests in precaution when all other firms in the industry also invest in precaution. The right-hand side of (5) is the firm's expected cost if the firm chooses to not invest in precaution while all other firms in the industry invest in precaution.

The inequality (5) can also be written as

(6) $C-P\cdot L<R(1)-R(0)\equiv\Delta_R(0)$.

According to expression (6), if all other firms in the industry are investing in precaution, a firm's best response is to invest in precaution (as opposed to not invest in precaution) when the expected benefit in the form of decreased losses due to industry reputation effects ($\Delta_R(0) \equiv R(1) - R(0)$) outweighs the cost of precaution net of expected liability damages the firm would have to pay in the absence of precaution ($C - P \cdot L$).

Similarly, industry configuration with no firm in the industry taking precaution ($m = n$) is a strict Nash equilibrium if no firm has incentive to deviate and instead take precaution, that is, if

(7) $C + R(n-1) > P \cdot L + R(n)$.

The left-hand side of inequality (7) is the firm's expected costs if the firm chooses to invest in precaution when the rest of the industry ($(n-1)$ firms) is not investing in precaution. The right-hand side of inequality (7) is the firm's expected cost if the firm chooses not to invest in precaution when all other firms in the industry are also not investing in precaution.

The inequality (7) can also be expressed as

(8) $C - P \cdot L > R(n) - R(n-1) \equiv \Delta_R(n-1)$.

Intuitively, if no other firm in the industry is investing in precaution, a firm's best response is to also not invest in precaution (as opposed to invest in precaution) when the expected benefit in the form of decreased losses due to industry reputation effects ($\Delta_R(n-1) \equiv R(n) - R(n-1)$) is smaller than the cost of precaution net of expected liability damages the firm would have to pay in the absence of precaution ($C - P \cdot L$).

Finally, industry configuration with $m \in \{1, \ldots, n-1\}$ firms not investing in precaution and $k \equiv n - m$ firms investing in precaution is a strict Nash equilibrium if, first, every firm investing in precaution finds it optimal not to abandon investing in precaution, that is, when

(9) $C + R(m) < P \cdot L + R(m+1)$

or, equivalently, when

(10) $C - P \cdot L < R(m+1) - R(m) \equiv \Delta_R(m)$,

and, second, every firm not investing in precaution has no incentive to instead invest in precaution, that is, when

(11) $C+R(m-1)>P\cdot L+R(m)$

or, equivalently, when

(12) $C-P\cdot L>R(m)-R(m-1)\equiv\Delta_R(m-1)$.

Industry configuration with $m\in\{1,\ldots,n-1\}$ firms in the industry not investing in precaution and $k\equiv n-m$ firms investing in precaution is therefore an equilibrium if $m\in\{1,\ldots,n-1\}$ simultaneously satisfies conditions (9) and (11), or, equivalently, conditions (10) and (12).[7,8]

By Lemma 1, we have $0<\Delta_R(0)<\Delta_R(1)<\ \ldots<\Delta_R(n-2)<\Delta_R(n-1)$. The following result, which follows immediately from the discussion above, summarizes the industry equilibrium for a given tort problem at hand.

Proposition 1: *Let m_{IND} be the (strict Nash) equilibrium number of firms that do not invest in precaution. Then,*

(i) $m_{IND}=0$ *iff* $C-P\cdot L<\Delta_R(0)$,
(ii) $m_{IND}\in\{1,\ldots,n-1\}$ *iff* $\Delta_R(m_{IND}-1)<C-P\cdot L<\Delta_R(m_{IND})$,
(iii) $m_{IND}=n$ *iff* $C-P\cdot L>\Delta_R(n-1)$,

where $\Delta_R(0)=P\cdot[0.5\alpha+\beta]$ *and* $\Delta_R(n-1)=P\cdot[0.5\alpha+\beta+\alpha P\cdot(n-1)]$.

Proposition 1 is illustrated graphically with Figures 1 and 2.[9] Intuitively, the larger the cost of precaution net of expected liability damages that the firm would have to pay in the absence of precaution ($C-P\cdot L$) for a given strength of industry reputation effects (as captured by

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[7] Industry configuration $m\in\{1,\ldots,n-1\}$ simultaneously satisfying conditions (9) and (11), or, equivalently, expressions (10) and (12), is evidently not unique when it comes to the identity of specific firms that invest in precaution and those that do not invest in precaution. In fact, there are $\binom{n}{m}$ strict Nash equilibria for any given $m\in\{1,\ldots,n-1\}$ that simultaneously satisfy conditions (9) and (11). Because the firms in the industry are identical, however, all of the equilibria for a given $m\in\{1,\ldots,n-1\}$ imply qualitatively the same behavior and have the same welfare repercussions (see Proposition 2 and Section 5).

[8] Our notion of industry equilibrium resonates closely with the concept of cartel stability (see, e.g., d'Aspremont et al. 1983, Donsimoni et al. 1986, Donsimoni 1985, Schaffer 1995, Nocke 2002).

[9] While $\Delta_R(m)$ is defined (only) on the set $\{1,2,\ldots,n\}$, we for graphical convenience in all of the figures illustrate $\Delta_R(m)$ as it were a continuous function defined on the entire interval $[0,n]$.

α and β), the larger the number of firms that do not invest in precaution in equilibrium (i.e. the smaller the equilibrium number of firms investing in precaution). Equivalently, the stronger the industry reputation effects for a given cost of precaution net of expected liability damages that the firm would have to pay in the absence of precaution (C–$P \cdot L$), the smaller the number of firms that do not invest in precaution in the equilibrium (i.e. the larger the equilibrium number of firms investing in precaution); see Figure 2.

4. Social Costs and Socially Optimal Industry Configuration

Social costs in our framework arise for three reasons. First, firms investing in precaution incur direct costs. When $n-m \equiv k$ firms invest in precaution, the total costs of precaution amount to $(n-m) \cdot C$. Second, with social harm per accident equal to H and with $m \equiv n-k$ firms in the industry not investing in precaution, the expected social losses due to accident-caused harm equal

$$(13) \qquad \sum_{j=0}^{m} \binom{m}{j} P^j (1-P)^{m-j} jH = mPH,$$

where the right-hand side of (13) equals the left-hand side because of the properties of the binomial distribution (see Appendix).

Third, expected industry-wide losses as a result of diminished industry reputation when m firms in the industry do not invest in precaution equal $n \cdot R(m)$. From the general equilibrium viewpoint, the decrease in firms' profits due to diminished reputation in the industry under consideration may be, at least in part, offset by an increase in profits of firms in an industry offering related products (if any) toward which the stakeholders rationally re-direct their attention. The process of re-direction of demand, however, entails consumers incurring welfare-reducing switching costs (see, e.g., Klemperer 1987; 1988: 390) and any industry employees seeking employment elsewhere (see, e.g., Barnett 2007: 7) incur labor market search costs. The losses in the industry hurt by diminished reputation are, therefore, never fully offset by any gains elsewhere in the economy. We thus let a proportion $\lambda>0$ of the firms' aggregate expected losses from diminished industry reputation ($n\cdot R(m)$) amount to net expected social costs.[10]

The magnitude of the parameter λ can be thought of as capturing the extent of industry specificity. λ will be small (close to zero) in situations when, following social harm-inducing accidents, industry stakeholders (consumers, employees) are able to re-direct their attention to another industry, which registers an increase in profits, at little cost. In contrast, λ will be comparatively larger in situations when there exist no, or very few, alternatives for the stakeholders of the industry experiencing socially harmful accidents.

With $m\equiv n-k$ firms in the industry not investing in precaution, the total expected social costs (expected social costs, in short) therefore equal

(14) $SC(m) = (n-m)\cdot C+m\cdot P\cdot H+\lambda\cdot n\cdot R(m).$

The following result summarizes the key properties of $SC(m)$.

Lemma 2: *Let* $\Delta_{SC}(m)\equiv SC(m+1)-SC(m)$ *and* $\Delta^2_{SC}(m)\equiv\Delta_{SC}(m+1)-\Delta_{SC}(m)$. *Then,*

(i) $\Delta_{SC}(m)>0$ *iff* $P\cdot H-C+n\lambda\Delta_R(m)>0$

(ii) $\Delta^2_{SC}(m)=n\lambda\Delta^2_R(m)>0$ *for all* $m\in\{0,1,\ldots,n\}$.

Aggregate precaution costs ($(n-m)C$) and the expected social losses from accident-caused harm (mPH) are linear in the number of firms not investing in precaution. Because expected industry-wide losses due to diminished industry reputation ($\lambda nR(m)$) are convex in the number of firms not investing in precaution (see Lemma 1), the expected social costs ($SC(m)$) are also convex in the number of firms not investing in precaution (Lemma 2, part (ii)).

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[10] None of our results change if we instead assume that the next expected social costs due to industry reputation effects are proportional to $R(m)$, rather than to $nR(m)$.

Whether expected social costs are increasing or decreasing in the number of firms not investing in precaution depends on the sign of $P\cdot H - C$. If $C < P\cdot H$, in which case it would have been socially optimal for all firms to invest in precaution in the absence of industry reputation effects, expected social costs are increasing in the number of firms not investing in precaution (Lemma 2, part (i)). On the other hand, if $C > P\cdot H$, in which case it would have been socially optimal for all firms to not invest in precaution in the absence of industry reputation effects, expected social costs might be decreasing as the number of firms not investing in precaution is small, and eventually increasing as the number of firms not investing in precaution becomes large.

Given the above considerations, the following result summarizes the socially optimal industry configuration in terms of the number of firms $m \equiv n-k$ not investing in precaution.

Proposition 2: *Let m_{SOC} be the number of firms in the industry not taking precaution such that the social costs* (14) *are minimized.*

(i) *If $C < P\cdot H$, then $m_{SOC}=0$ for any $\lambda>0$.*

(ii) *If $C > P\cdot H$, then*

  (a) $m_{SOC}=0$ *iff* $C-P\cdot H < n\lambda\Delta_R(0)$,

  (b) $m_{SOC}\in\{1,\ldots,n-1\}$ *iff* $n\lambda\Delta_R(m_{IND}-1) < C-P\cdot H < n\lambda\Delta_R(m_{IND})$,

  (c) $m_{SOC}=n$ iff $C-P\cdot H > n\lambda\Delta_R(n-1)$,

where $\Delta_R(0)=P\cdot[0.5\alpha+\beta]$ *and* $\Delta_R(n-1)=P\cdot[0.5\alpha+\beta+\alpha P\cdot(n-1)]$.

Proposition 2 is illustrated with Figures 3 and 4. (The shape of $n\lambda\Delta_R(m)$ follows directly from the properties of $\Delta_R(m)$ summarized in Lemma 1.) The larger the cost of precaution net of expected accident-related social harm caused by a firm in the absence of precaution ($C-P\cdot H$), the larger the number of firms that should, from the social welfare viewpoint, abstain from investing in precaution (and thus the smaller the socially desirable number of firms investing in precaution). Equivalently, when the cost of precaution exceeds the expected accident-related social harm caused by a firm in the absence of precaution ($C-P\cdot H>0$), the stronger the industry reputation effects, the smaller the socially optimal number of firms that should not be investing in precaution (and thus the larger the socially desirable number of firms investing in precaution).

5. Equilibrium vs. Socially Optimal Industry Configuration: Comparative Statics

The analysis in Sections 3 and 4 reveals that, for a given tort problem at hand, the equilibrium industry configuration, as captured by m_{IND} (see Proposition 1), in general need not coincide with the socially optimal industry configuration, as captured by m_{SOC} (see Proposition 2). We say that the equilibrium industry configuration and the socially optimal industry configuration are *aligned* whenever m_{IND}=m_{SOC}, and *misaligned* when $m_{IND} \neq m_{SOC}$. In this section, we examine how a liability regime and industry reputation effects—the two forces shaping the firms' incentives to invest in precaution—determine whether the equilibrium industry configuration is aligned or misaligned with the socially optimal industry configuration.

We first focus on the impact of industry reputation effects for a given liability regime (Section 5.1). We then explore the impact of introduction of a strict liability rule given the presence of industry reputation effects (Section 5.2).

5.1. The Impact of Industry Reputation Effects

We first characterize equilibrium industry configuration and deduce its social welfare properties in a counterfactual environment in which there are no industry reputation effects, that is, the standard scenario examined in the literature (see, e.g., Shavell (2004, 2007); Cooter and Ulen (2012); Miceli (2008)) when each of the *n* firms optimally chooses whether to invest in precaution without any regard for the actions taken by other firms in the industry.

In the absence of industry reputation effects, a firm will invest in precaution if and only if the cost of investing in precaution (C) is smaller than the firm's expected cost from not investing in precaution ($P \cdot L$). In contrast, from the social welfare point of view, a firm should invest in precaution if and only if the cost of investing in precaution is smaller than the expected social loss in the absence of precaution ($P \cdot H$). We thus have the following result:[11]

Lemma 3: *In the absence of industry reputation effects (i.e., when* $\alpha=\beta\equiv 0$*),*

(i) if $C<P \cdot L<P \cdot H$, then $m_{IND}=m_{SOC}=0$;

(ii) if $P \cdot L<C<P \cdot H$, then $m_{IND}=n$ and $m_{SOC}=0$;

(iii) if $P \cdot L<P \cdot H<C$, then $m_{IND}=m_{SOC}=n$.

According to Lemma 3, in the absence of industry reputation effects, industry equilibrium coincides with the socially optimal industry configuration either when a firm's cost of precaution is small relative to the expected liability damages and the expected social costs or when the cost of precaution is large relative to both the expected social costs and the expected liability damages. In contrast, industry equilibrium does not coincide with the socially optimal industry configuration when the cost of precaution exceeds expected liability damages but is at the same time smaller than the expected social harm in the case of an accident.

We now examine how the existence of industry reputation effects shapes the relationship between the equilibrium and socially optimal industry configuration in the presence of a strict liability rule for a given tort problem under consideration.

In the scenario when, without industry reputation effects, all firms would have chosen to invest in precaution and the resulting configuration would have been socially optimal ($C<P \cdot L<P \cdot H$; see Lemma 3, part (i)), the presence of industry reputation effects merely increases a firm's incentive to invest in precaution. Industry equilibrium, therefore, involves all firms investing in precaution (see part (i) of Proposition 1).

Likewise, when $C<P \cdot H$, the social costs are increasing with the number of firms not investing in precaution (see Lemma 2). Thus, the socially optimal industry configuration both in

[11] Since all firms in the industry are (ex ante) identical, industry equilibrium and socially optimal industry configuration in the absence of industry reputation effects can be characterized by focusing on a representative firm.

the presence, and in the absence, of industry reputation effects involves all firms investing in precaution (see Proposition 2, part (i)). We therefore have the following result, illustrated in Figure 5:

Proposition 3: *If $C<P{\cdot}L<P{\cdot}H$, the presence of industry reputation effects, relative to the scenario without industry reputation effects, alters neither m_{IND} nor m_{SOC}. m_{IND} and m_{SOC} are aligned both in the presence and in the absence of industry reputation effects.*

In contrast, in the scenario when, without industry reputation effects, no firm invests in precaution and the socially optimal industry configuration involves all firms investing in precaution ($P{\cdot}L<C<P{\cdot}H$; see Lemma 2, part (ii)), the presence of industry reputation effects may affect the alignment between the equilibrium and socially optimal industry configuration.

With $C<P{\cdot}H$, much like in the scenario described by Proposition 3, the socially optimal industry configuration in the presence of industry reputation effects involves all firms investing in precaution (see Proposition 2, part (i)). The equilibrium industry configuration when $C>P{\cdot}L$, however, depends on the strength of industry reputation effects.

When industry reputation effects are weak (α and β are small, and thus $\Delta_R(m)$ is small for a given m; see Lemma 1), it is plausible that $C>P{\cdot}L+\Delta_R(n-1)$, where $\Delta_R(n-1)=P{\cdot}[0.5\alpha+\beta+\alpha P{\cdot}(n-1)]>0$, in which case industry equilibrium is such that no firm invests in precaution (see Proposition 1, part (iii)). When $C>P{\cdot}L+\Delta_R(n-1)$, industry reputation effects are too weak to steer the industry equilibrium toward the socially optimal industry configuration.

However, when industry reputation effects are strong (α and β are large, and thus $\Delta_R(m)$ is large for a given m; see Lemma 1), $C<P{\cdot}L+\Delta_R(n-1)$, in which case the industry equilibrium involves a positive number of firms taking precaution (see Proposition 1, part (ii)). In particular, when industry reputation effects are sufficiently strong, $C<P{\cdot}L+\Delta_R(0)$. The industry equilibrium

then involves all firms investing in precaution (see Proposition 1, part (iii)), which in this case coincides with the socially optimal industry configuration. The above analysis leads to the following result, illustrated in Figure 6:

Proposition 4: *If $P{\cdot}L<C<P{\cdot}H$, the presence of industry reputation effects may steer m_{IND} toward m_{SOC} when m_{IND} and m_{SOC} would have been misaligned in the absence of industry reputation effects.*

Finally, in the scenario when, without industry reputation effects, no firm invests in precaution and the resulting industry configuration is socially optimal ($P{\cdot}L<P{\cdot}H<C$; see Lemma 3, part (iii)), the presence of industry reputation effects in general has an ambiguous impact on the industry equilibrium and the socially optimal industry configuration.

When the extent of industry specificity is high, so that the expected losses to firms and industry stakeholders from diminished industry reputation are an important part of expected social costs (i.e. when $\lambda>n^{-1}$), the industry equilibrium in the presence of reputation effects in general involves fewer firms investing in precaution than socially desirable ($m_{IND}>m_{SOC}$).[12] Intuitively, at the socially optimal number of firms not investing in precaution (m_{SOC}), the cost of precaution net of a firm's expected liability damages in the case of an accident is greater than the increase in losses due to industry reputation effects if a firm chooses not to invest in precaution ($C-P{\cdot}L>\Delta_R(m_{SOC})$). A firm investing in precaution thus has an incentive to abandon investing in precaution, implying that the (strict Nash) equilibrium m_{IND} must exceed m_{SOC}. Figure 7 illustrates this result.

In contrast, when the extent of industry specificity is low, so that expected losses to firms and industry stakeholders from diminished industry reputation account for only a small portion

[12] The exception occurs when either $C-P{\cdot}L<\Delta_R(0)$ or when $C-P{\cdot}H>n\lambda\Delta_R(n-1)$. In the former case, all firms take precaution in the equilibrium and such an industry configuration is also socially optimal ($m_{IND}=m_{SOC}=0$). In the latter case, no firm takes precaution in the equilibrium and such an industry configuration is also socially optimal ($m_{IND}=m_{SOC}=n$).

of expected social costs (i.e. when $\lambda<n^{-1}$), industry equilibrium in the presence of industry reputation effects may in general involve either a smaller or a larger number of firms investing in precaution than the socially optimal industry configuration. Figure 8, for example, illustrates a scenario when, in the presence of industry reputation effects, industry equilibrium involves all firms investing in precaution ($C-P\cdot L<\Delta_R(0)$; see Proposition 1, part (i)) while the socially optimal industry configuration requires that no firm invests in precaution ($C-P\cdot H>n\lambda\Delta_R(n-1)$; see Proposition 2, part (ii)(c)). Therefore:

Proposition 5: *If $P\cdot L<P\cdot H<C$, the presence of industry reputation effects in general steers m_{IND} away from m_{SOC} when m_{IND} and m_{SOC} would have been aligned in the absence of industry reputation effects.*

In sum, Propositions 3-5 suggest that the impact of industry reputation effects is contingent on the nature of the particular tort problem at hand. Industry reputation effects have no impact on the alignment between the equilibrium and the socially optimal industry configuration when, in the absence of industry reputation effects, all firms would have invested in precaution and doing so would have been socially optimal (Proposition 3).

In contrast, industry reputation effects may align the equilibrium with the socially optimal industry configuration when, in the absence of industry reputation effects, the liability regime fails to incentivize firms to invest in precaution when it would have been socially optimal for all firms to invest in precaution (Proposition 4). The presence of industry reputation effects can, therefore, substitute for a sub-optimal liability regime.

Finally, the presence of industry reputation effects is undesirable when it misaligns the equilibrium and the socially optimal industry configuration. This occurs when, in the absence of industry reputation effects, no firm would have had an incentive to invest in precaution and no firm investing in precaution would have been the socially optimal industry configuration (Proposition 5).

5.2. The Impact of a Strict Liability Rule

In the counterfactual scenario without a liability regime, a firm's expected liability damages equal zero: $L \equiv 0$. We investigate how, given industry reputation effects, the introduction of the strict liability rule L such that $0<L<H$ (see Section 2) impacts the extent of alignment between the equilibrium and the socially optimal industry configuration.

The socially optimal industry configuration entails all firms in the industry investing in precaution when either a firm's cost of precaution is smaller than the expected social harm from an accident ($C<P \cdot H$) or when a firm's cost of precaution exceeds the expected social harm from an accident ($C>P \cdot H$) and firms' and industry stakeholders' losses due to diminished industry reputation lead to non-negligible net social costs ($\lambda>n^{-1}$); see Proposition 2. Figures 9 and 10 illustrate these scenarios.

When for a given cost of precaution the industry reputation effects are not excessively strong, the equilibrium industry configuration in the absence of a liability regime ($L \equiv 0$) under any of the above two scenarios, in contrast with the socially optimal industry configuration, entails a strictly positive number of firms that do not invest in precaution (see Proposition 1, parts (ii) and (iii)). Under these conditions, the introduction of a strict liability rule increases the incentives of firms to invest in precaution, and, as a consequence, possibly fully aligns industry equilibrium with the socially optimal industry configuration. This is illustrated in Figures 9 and 10. We thus have the following result:

Proposition 6: *In the presence of industry reputation effects, when either $C<P \cdot H$ or when $C>P \cdot H$ and $\lambda>n^{-1}$, the introduction of the strict liability rule may steer m_{IND} toward m_{SOC} when m_{IND} and m_{SOC} would have been misaligned in the absence of a liability regime.*

When a firm's costs of precaution are greater than the expected social harm from an accident ($C>P\cdot H$) and, for a given strength of industry reputation effects, firms' and industry stakeholders' losses due to diminished industry reputation give rise to small net social costs ($\lambda<n^{-1}$), the socially optimal industry configuration may entail $m_{SOC}=m''$ firms abstain from investing in precaution and $k\equiv n-m''$ firms investing in precaution (see Proposition 2, part (ii)(b)). Industry equilibrium in the absence of a liability regime ($L\equiv 0$) then coincides with the socially optimal industry configuration if $\Delta_R(m''-1)<C-P\cdot L<\Delta_R(m'')$ (see Proposition 1, part (ii)). This situation is illustrated in Figure 11.

Under the above conditions, the introduction of a strict liability rule may increase the equilibrium number of firms investing in precaution, thereby steering industry equilibrium away from the socially optimal industry configuration. In particular, the implementation of a strict liability rule shifts the industry equilibrium toward a point when all firms invest in precaution (while the socially optimal industry configuration, in contrast, dictates that only $k\equiv n-m''$ firms should be investing in precaution) when $C-P\cdot L<\Delta_R(0)$ (see Proposition 1, part (i)). Figure 11 portrays this scenario. We therefore have the following result:

Proposition 7: *In the presence of industry reputation effects, when $C>P\cdot H$ and $\lambda<n^{-1}$, the introduction of the strict liability rule may steer m_{IND} away from m_{SOC} when m_{IND} and m_{SOC} would have been aligned in the absence of a liability regime.*

Observe that in the situation depicted by Figure 11, the introduction of the strict liability rule in the absence of industry reputation effects would have had no effect: in the absence of industry reputation effects, no firm would have invested in precaution with the strict liability rule in place or not, and such an industry configuration would have been socially optimal.

In sum, in the presence of industry reputation effects, the introduction of a strict liability rule is desirable, in the sense that it may align industry equilibrium with the socially optimal industry configuration, when in the absence of a liability regime industry equilibrium involves too few firms investing in precaution (Proposition 6). In contrast, when the socially optimal industry configuration involves only a fraction of firms, or no firm, investing in precaution, the introduction of a strict liability rule may push the industry equilibrium toward a socially suboptimal configuration where too many firms invest in precaution (Proposition 7). That is, introduction of a strict liability regime may in the presence of industry reputation effects be detrimental as it can misalign the equilibrium and the socially optimal industry configurations.

6. Conclusion

When "one firm's actions influence the judgments observers make of another firm or an industry as a whole…the fates of firms in the industry are intertwined because all firms suffer when any firm engages in actions that damage the industry's shared reputation" (Barnett and King 2008: 1152). As a result of "one firm's error…reflect[ing] negatively on its rivals", firms are "forced to concern themselves not only with their own conduct but also with that of their rivals" (Barnett 2007: 3). The presence of industry reputation effects, therefore, generates firm interdependence, which in turn requires that the problem of torts be analyzed within a framework explicitly recognizing the strategic nature of firm behavior.

This paper has developed a model of torts to examine how the presence of industry reputation effects shapes firms' decisions to invest in precaution reducing the likelihood of social harm. We have characterized industry equilibrium for a given tort problem at hand and contrasted it with the socially optimal industry configuration, as captured by the socially optimal number of firms investing in precaution.

We have shown that, under some circumstances, the fact that firms within an industry are 'tarred by the same brush' may substitute for a suboptimal liability regime in that the presence of industry reputation effects may steer the industry equilibrium toward the socially optimal industry configuration when industry equilibrium and the socially optimal industry configuration would have been misaligned in the absence of industry reputation effects. Under other circumstances, however, the presence of industry reputation effects misaligns the equilibrium and the socially optimal industry configuration when the two would have been aligned in the absence of industry reputation effects.

We have further demonstrated that the impact of introducing a liability regime in the presence of industry reputation effects is in general also ambiguous and contingent on the specifics of the tort problem at hand. That is, while the introduction of a strict liability rule may steer the industry equilibrium toward the socially optimal industry configuration under some circumstances, imposition of a strict liability rule may under other circumstances push the industry equilibrium away from the socially desirable outcome.

In the presence of industry reputation effects, firms may take further actions to attempt to escape the common fate. This involves actively engaging in a process of "preferential detachment" (Yu et al. 2008), which may include adoption and enforcement of self-regulatory standards (see, e.g., King et al. 2002; Barnett 2007; Barnett and King 2008; Pouliot and Sumner 2010). Future work could extend our analysis to examine the reasons for, and repercussions of, such 'institutionalized' strategic responses of industry participants in the presence of common reputation effects, as well as the interaction of these 'private order' institutional solutions with the functioning of tort law and government-imposed regulations.

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Figures

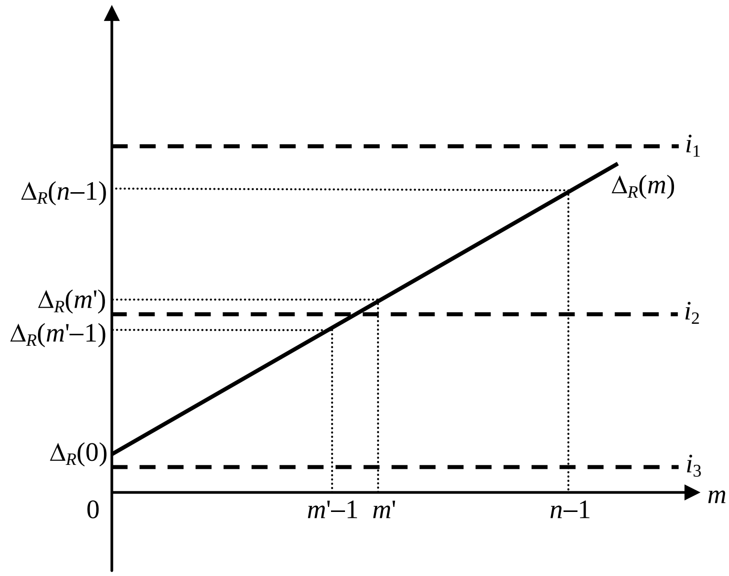

Figure 1: Illustration of Proposition 1. $C–P·L=i_1$ implies $m_{IND}=n$. $C–P·L=i_2$ implies $m_{IND}=m'$. $C–P·L=i_3$ implies $m_{IND}=0$.

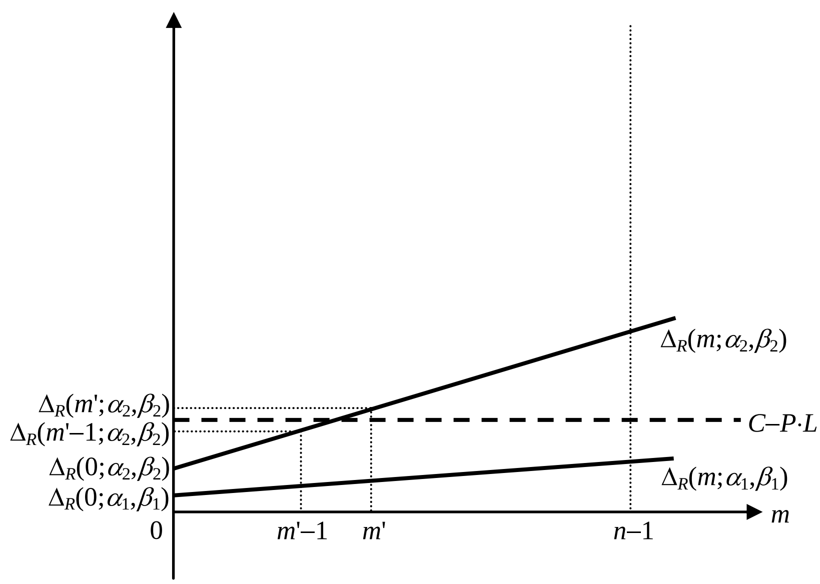

Figure 2: Illustration of Proposition 1. $(\alpha,\beta)=(\alpha_1,\beta_1)$ implies $m_{IND}=n$. $(\alpha,\beta)=(\alpha_2,\beta_2)$ implies $m_{IND}=m'$. $\alpha_2>\alpha_1$, $\beta_2>\beta_1$.

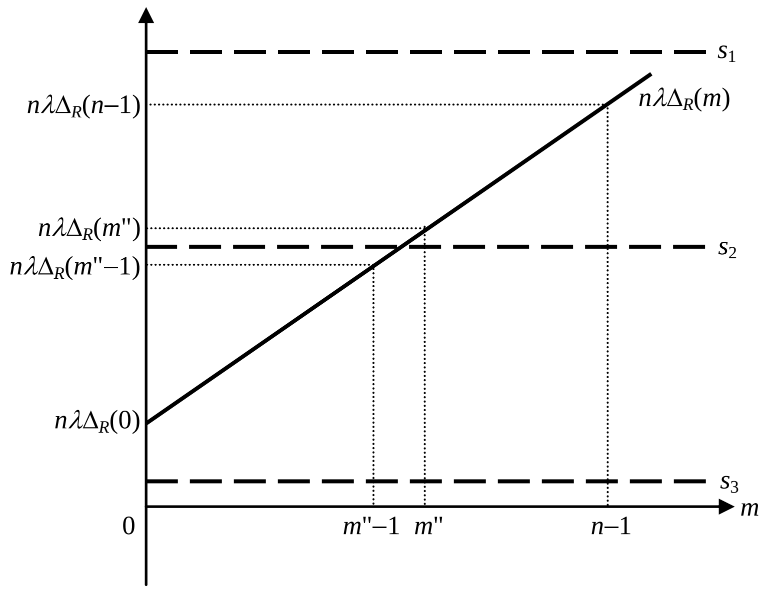

Figure 3: Illustration of Proposition 2. $C{-}P{\cdot}H{=}s_1$ implies $m_{SOC}{=}n$. $C{-}P{\cdot}H{=}s_2$ implies $m_{SOC}{=}m''$. $C{-}P{\cdot}H{=}s_3$ implies $m_{SOC}{=}0$.

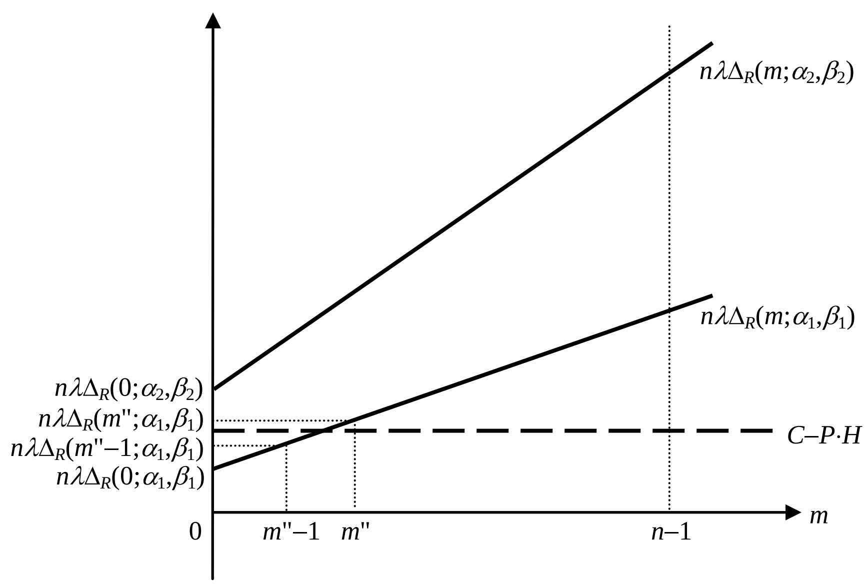

Figure 4: Illustration of Proposition 2. $(\alpha,\beta){=}(\alpha_1,\beta_1)$ implies $m_{SOC}{=}m''$. $(\alpha,\beta){=}(\alpha_2,\beta_2)$ implies $m_{SOC}{=}0$. $\alpha_2{>}\alpha_1$, $\beta_2{>}\beta_1$.

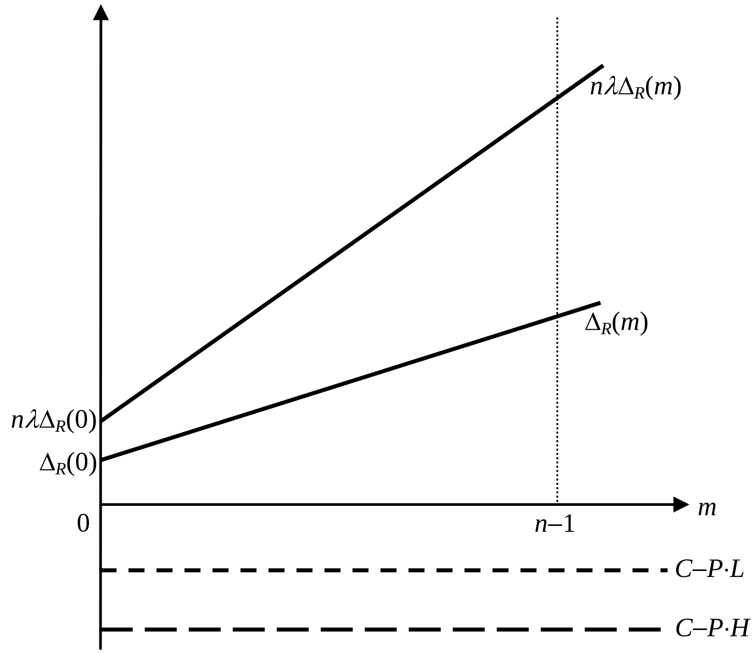

Figure 5: A scenario with $C<P{\cdot}L<P{\cdot}H$ when the presence of industry reputation effects affects neither the equilibrium nor the socially optimal industry configuration. $m_{IND}=m_{SOC}=0$ both in the presence and in the absence of industry reputation effects. Figure assumes $\lambda>n^{-1}$.

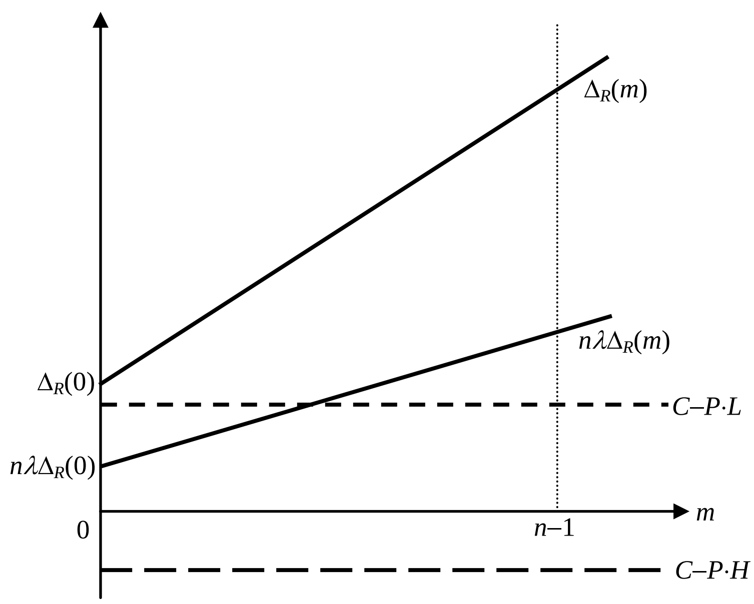

Figure 6: A scenario with $P{\cdot}L<C<P{\cdot}H$ when the presence of industry reputation effects steers the industry equilibrium toward the socially optimal industry configuration. $m_{SOC}=0$ both in the presence and in the absence of industry reputation effects. In the absence of industry reputation effects, $m_{IND}=n$. In the presence of industry reputation effects, $m_{IND}=0$. Figure assumes $\lambda<n^{-1}$.

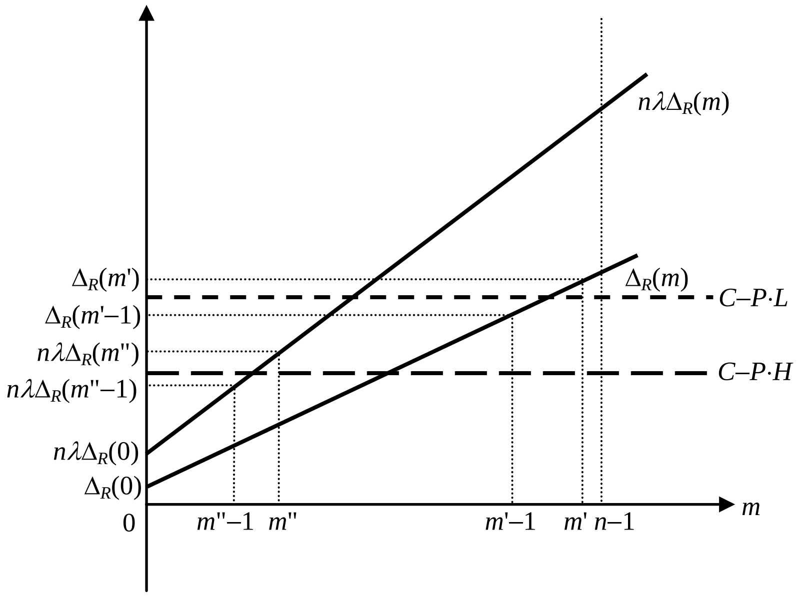

Figure 7: A scenario with $P{\cdot}L<P{\cdot}H<C$ and $\lambda>n^{-1}$ when the presence of industry reputation effects steers the industry equilibrium away from the socially optimal industry configuration. In the absence of industry reputation effects, $m_{IND}=m_{SOC}=0$. In the presence of industry reputation effects, $m_{SOC}=m''<m'=m_{IND}$.

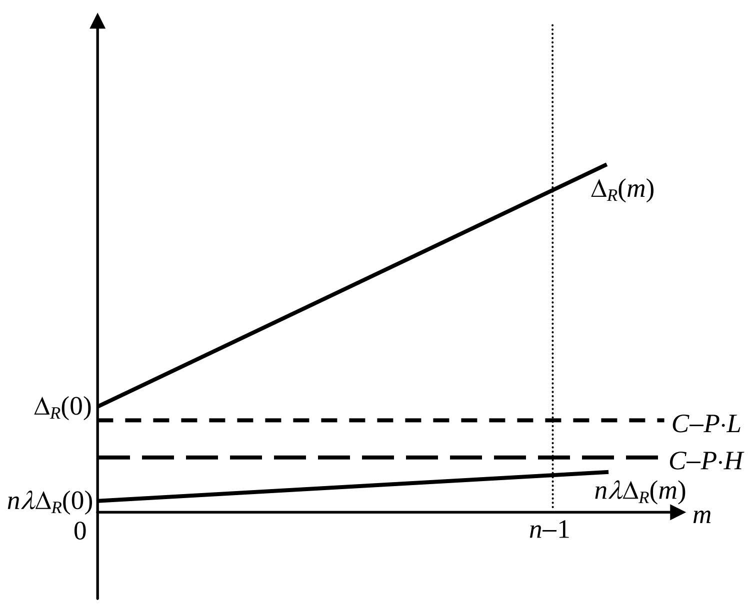

Figure 8: A scenario with $P{\cdot}L<P{\cdot}H<C$ and $\lambda<n^{-1}$ when the presence of industry reputation effects steers the industry equilibrium away from the socially optimal industry configuration. In the absence of industry reputation effects, $m_{IND}=m_{SOC}=0$. In the presence of industry reputation effects, $m_{SOC}=n$ and $m_{IND}=0$.

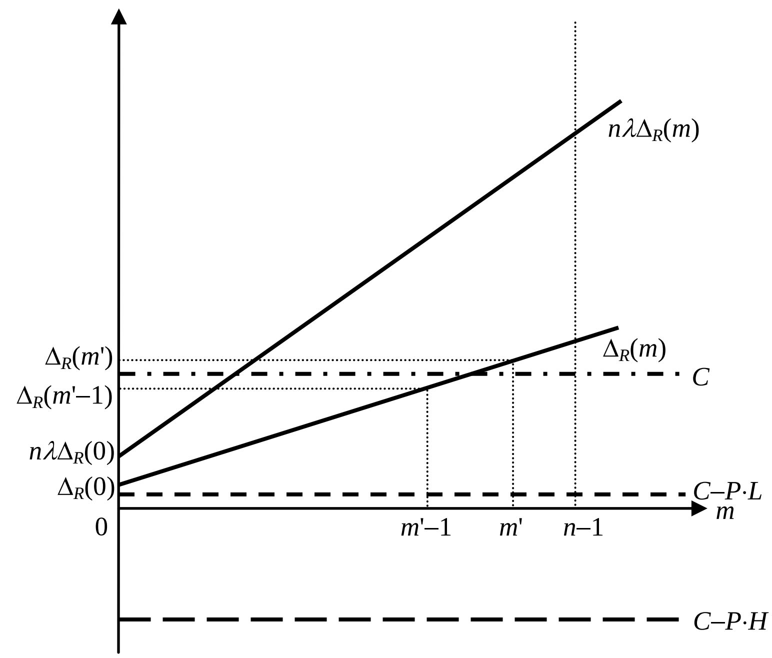

Figure 9: A scenario with $C<P\cdot H$ when the introduction of the strict liability rule steers the industry equilibrium toward the socially optimal industry configuration. $m_{SOC}=0$ regardless of whether a liability regime is in place or not. In the absence of a liability regime ($L\equiv0$), $m_{IND}=m'>0$. After the introduction of the strict liability rule ($0<L<H$), $m_{IND}=0$. Figure assumes $\lambda>n^{-1}$.

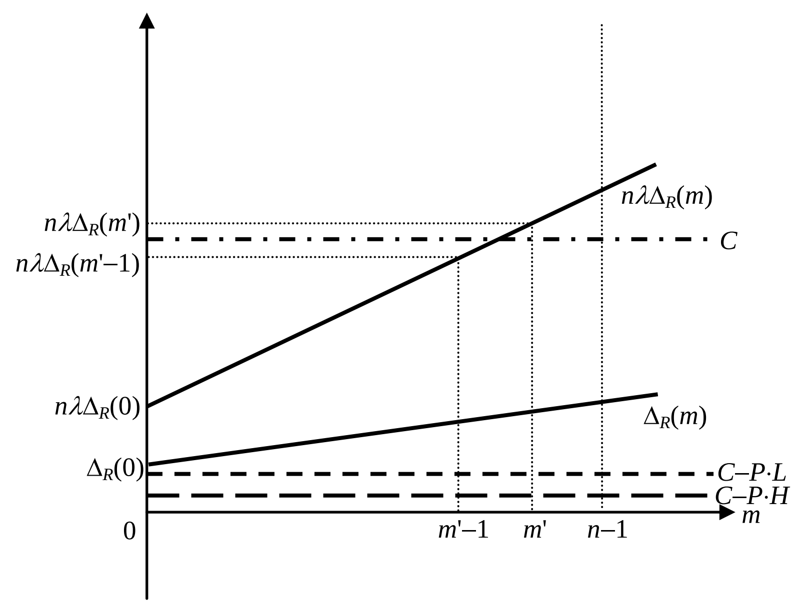

Figure 10: A scenario with $C>P\cdot H$ and $\lambda>n^{-1}$ when the introduction of the strict liability rule steers the industry equilibrium toward the socially optimal industry configuration. $m_{SOC}=0$ regardless of whether a liability regime is in place or not. In the absence of a liability regime ($L\equiv0$), $m_{IND}=m'>0$. After the introduction of the strict liability rule ($0<L<H$), $m_{IND}=0$.

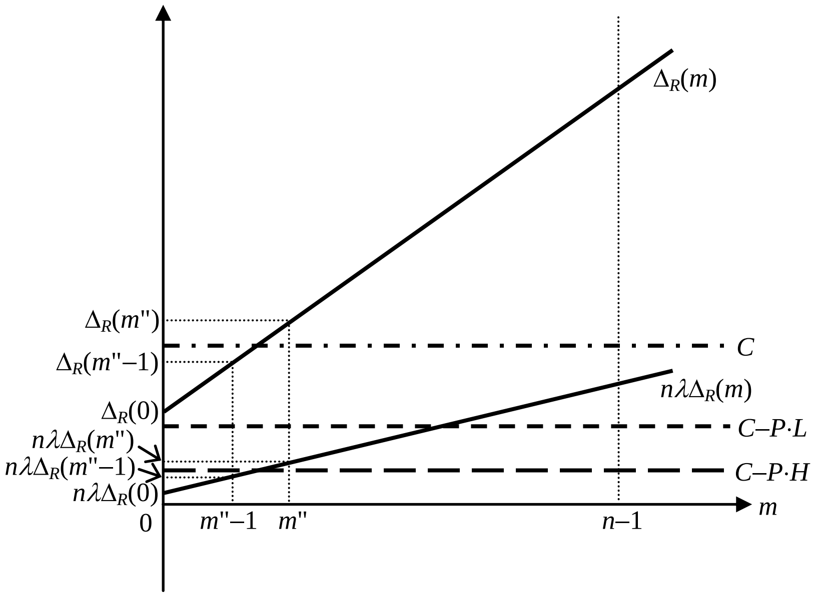

Figure 11: A scenario with $C>P\cdot H$ and $\lambda<n^{-1}$ when the introduction of the strict liability rule in the presence of industry reputation effects steers the industry equilibrium away from the socially optimal industry configuration. $m_{SOC}=m''$ regardless of whether a liability regime is in place or not. In the absence of a liability regime ($L\equiv0$), $m_{IND}=m''$. After the introduction of the strict liability rule ($0<L<H$), $m_{IND}=0$.

Appendix

Derivation of expression (4):

Given (2), expression (3) becomes

$$R(m)=\sum_{j=0}^{m}\binom{m}{j}P^{j}(1-P)^{m-j}[0.5\alpha j^{2}+\beta j]$$

$$=0.5\alpha\sum_{j=0}^{m}\binom{m}{j}P^{j}(1-P)^{m-j}j^{2}+\beta\sum_{j=0}^{m}\binom{m}{j}P^{j}(1-P)^{m-j}j$$

$$=0.5\alpha\mathrm{E}[X^{2}]+\beta\mathrm{E}[X],$$

where X is a random variable following a binomial distribution with $m\equiv n-k$ independent (Bernoulli) trials with success probability P. Drawing on the properties of binomially distributed random variables (see, e.g., Mood et al. 1974: 88-89), $\mathrm{E}[X]=mP$ and $\mathrm{Var}[X]=mP(1-P)$. Because $\mathrm{Var}[X]\equiv\mathrm{E}[X^2]-(\mathrm{E}[X])^2$, we thus have $\mathrm{E}[X^2]=mP(1-P+mP)$. Using these facts and collecting terms,

$$R(m)=m^{2}0.5\alpha P^{2}+m[0.5\alpha P(1-P)+\beta P],$$

which is expression (4). □

Lemma A1:

Let $f(x)=ax^2+bx+c$, where $x\in\{0,1,2,\dots\}$. Then,

(i) $\Delta_f(x)\equiv f(x+1)-f(x)=a(2x+1)+b$,

(ii) $\Delta^2{}_f(x)\equiv\Delta_f(x+1)-\Delta_f(x)=2a$.

Proof: Straightforward, thus omitted. □

Proof of Lemma 1:

To prove Lemma 1, we use Lemma A1 above. For $R(m)$ in (4), which is quadratic in m, let $a\equiv 0.5\alpha P^2$, $b\equiv 0.5\alpha P(1-P)+\beta P$, and $c\equiv 0$. Thus, from Lemma A1, part (i),

$$\Delta_R(m)\equiv R(m+1)-R(m)=0.5\alpha P^{2}(2m+1)+[0.5\alpha P(1-P)+\beta P]>0,$$

which proves part (i) of Lemma 1. From Lemma A1, part (ii),

$$\Delta^{2}{}_R(m)\equiv\Delta_R(m+1)-\Delta_R(m)=\alpha P^{2}>0,$$

which proves part (ii) of Lemma 1. Finally,

$$\partial\Delta_R(m)/\partial\alpha=m^{2}0.5P^{2}+m0.5P(1-P)>0,\ \partial\Delta_R(m)/\partial\beta=mP>0,$$

which proves part (iii) of Lemma 1. □

Proof of Proposition 1:

Follows immediately from the discussion preceding Proposition 1, and is thus omitted. □

Derivation of expression (13):

With social harm per accident equal to H and with $m \equiv n-k$ firms in the industry not investing in precaution, the expected social losses due to accidents equal

$$\sum_{j=0}^{m} \binom{m}{j} P^j (1-P)^{m-j} \cdot j \cdot H = H \sum_{j=0}^{m} \binom{m}{j} P^j (1-P)^{m-j}\, j = H \cdot \mathrm{E}[X] = HmP,$$

where X is a random variable following a binomial distribution with $m \equiv n-k$ independent (Bernoulli) trials with success probability P, and thus $\mathrm{E}[X]=mP$; see derivation of expression (4) above. □

Proof of Lemma 2:

Rewrite expression (14) as

$$SC(m) = nC+(P\cdot H-C)m+\lambda nR(m),$$

where $R(m)$ is defined in (4). Then,

$$\Delta_{SC}(m) \equiv SC(m+1)-SC(m)=(P\cdot H-C)+\lambda n\Delta_R(m),$$

where $\Delta_R(m) \equiv R(m+1)-R(m)>0$ (see Lemma 1). Thus, $\Delta_{SC}(m)>0$ if and only if

$$(P\cdot H-C)+\lambda n\Delta_R(m)>0,$$

which proves part (i) of Lemma 2.

Given the expression for $\Delta_{SC}(m)$ above, we have

$$\Delta^2_{SC}(m) \equiv \Delta_{SC}(m+1)-\Delta_{SC}(m)=n\lambda\Delta^2_R(m),$$

which is strictly positive because $\Delta^2_R(m)>0$ from Lemma 1. This proves part (ii) of Lemma 2. □

Proof of Proposition 2:

From Lemma 2, we know that $\Delta^2_{SC}(m)>0$ for all $m \in \{0,1,\ldots,n\}$. Thus, we have

$$\Delta_{SC}(0)<\Delta_{SC}(1)< \ldots <\Delta_{SC}(n-2)<\Delta_{SC}(n-1).$$

If $C<P\cdot H$, then $\Delta_{SC}(0)=P\cdot H-C+n\cdot\lambda\cdot\Delta_R(0)>0$ because $\Delta_R(0)>0$ (see Lemma 1). Thus, we have $0<\Delta_{SC}(0)<\Delta_{SC}(1)< \ldots <\Delta_{SC}(n-2)<\Delta_{SC}(n-1)$: $SC(m)$ is strictly increasing in $m \in \{0,1,\ldots,n\}$, and therefore $m_{SOC}=0$. This proves part (i) of Proposition 2.

If $C>P\cdot H$, three possible cases arise. First, we might have

$$0<\Delta_{SC}(0)<\Delta_{SC}(1)< \ldots <\Delta_{SC}(n-2)<\Delta_{SC}(n-1).$$

The above chain of inequalities reduces to $0<\Delta_{SC}(0)$, or, equivalently, to

$$C-P\cdot H<n\lambda\Delta_R(0).$$

With $SC(m)$ strictly increasing in $m\in\{0,1,\ldots,n\}$, $m_{SOC}=0$.

As a second possibility, we might have

$$\Delta_{SC}(0)<\Delta_{SC}(1)<\ldots<\Delta_{SC}(n-2)<\Delta_{SC}(n-1)<0.$$

The above chain inequalities reduces to $\Delta_{SC}(n-1)<0$, or, equivalently, to

$$C-P\cdot H>n\lambda\Delta_R(n-1).$$

With $SC(m)$ now strictly decreasing in $m\in\{0,1,\ldots,n\}$, $m_{SOC}=n$.

As a third and final possibility, we might have

$$\Delta_{SC}(0)<\ldots<\Delta_{SC}(m''-1)<0<\Delta_{SC}(m'')<\ldots<\Delta_{SC}(n-1),$$

where $m''\in\{1,\ldots,n-1\}$. The above chain of inequalities reduces to $\Delta_{SC}(m''-1)<0<\Delta_{SC}(m'')$, or, equivalently, to

$$P\cdot H-C+n\lambda\Delta_R(m''-1)<0<P\cdot H-C+n\lambda\Delta_R(m'')$$

and finally to

$$n\lambda\Delta_R(m''-1)<C-P\cdot H<n\lambda\Delta_R(m'').$$

With $SC(m)$ now first decreasing and eventually increasing in $m\in\{0,1,\ldots,n\}$, $m_{SOC}=m''$. This proves part (ii) of Proposition 2. □

Proof of Lemma 3:

Trivial, thus omitted. □

Proof of Propositions 3-7:

Follows immediately from the discussion preceding each of the Propositions 3-7 and from the corresponding figures. □