Ann Oper Res (2016) 237:27–40
DOI 10.1007/s10479-014-1684-5

The strategic interaction between a company and the government surrounding disasters

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Published online: 12 August 2014

Abstract We analyze the tradeoff between safety and production. The government chooses safety effort and tax rate in the first stage, and then the company strikes a balance between safety effort and production in the second stage. The government, representing the general public, earns taxes on production. Both players' safety efforts mitigate the negative impact of a disaster. The disaster probability is modeled as a contest between the disaster magnitude and the two players' safety efforts. Seven propositions are developed. First, as the safety effort of one player approaches infinity, the marginal change in the other player's safety effort, with respect to the first player's safety effort, approaches zero. Second, an infinitely large safety effort by any player causes the disaster probability and the negative impact of the disaster to decrease toward a constant. Third, as one player's safety effort approaches infinity, the other player's safety effort approaches zero. Fourth, the two players' safety efforts are strategic substitutes so that an increase in one player's safety effort decreases the other player's safety effort. This enables the players to free ride on each other's safety efforts. Fifth, higher tax rate causes the company to exert higher safety effort. Sixth, with maximum tax rate the company focuses exclusively on safety effort and generates no profit. Seventh, the company's safety effort is inverse U shaped in the disaster magnitude.

This research was partially supported by the United States Department of Homeland Security (DHS) through the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) under award number 2010-ST-061-RE0001. This research was also partitially supported by the United States National Science Foundation (NSF) award numbers 1334930 and 1200899. However, any opinions, findings, and conclusions or recommendations in this document are those of the authors and do not necessarily reflect views of the DHS, CREATE, or NSF. Author names were listed alphabatically by last name.

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Keywords Disaster · Safety effort · Production · Profit · Taxation · Conflict · Contest

JEL Classification C72 · D72 · D74 · H21 · H71

List of symbols

R	Company's resource
E	Company's productive effort
S	Company's safety effort
s	Government's safety effort
A	Company's unit cost of production
B	Company's unit cost of safety effort
$H(S)$	Production function
b	Government's unit cost of safety effort
D	Disaster magnitude
$p(D, S, s)$	Disaster probability
$F(D, S, s)$	Scaling function for how the company is negatively affected by disaster
$f(D, S, s)$	Scaling function for how the government is negatively affected by disaster
τ	Taxation percentage variable chosen by the government
u	Government's expected profit
U	Company's expected profit

1 Introduction

Companies face important challenges when balancing production efficiency against safety effort.[1] Examples are the oil spills by BP in the Gulf of Mexico between April 20–July 15, 2010[2] and by Exxon Valdez in Alaska on March 24, 1989.[3,4] We consider how a company determines a tradeoff or balance between production and safety effort. A government also exerts safety effort, and taxes the company's production. The objectives of safety efforts are to decrease the adverse impact of a disaster. We analyze the players' incentives to free ride on each other's safety efforts. That is, a player may exert low or no safety effort to benefit

[1] See http://www.infoplease.com/ipa/A0001451.html for major oil spills since 1967, and http://news.yahoo.com/s/ac/20110317/sc_ac/8079848_worst_oil_spills_in_history for the five worst oil spills in history. The gravity of disasters can be measured according to economic loss, human loss, and symbolic loss. The July 6, 1988 North Sea off Scotland Occidental Petroleum's Piper Alpha rig disaster killed 167 people, http://en.wikipedia.org/wiki/Piper_Alpha#cite_note-2. The North Sea off Norway March 27, 1980 capsize of the Alexander L. Kielland platform killed 123 people, http://en.wikipedia.org/wiki/Alexander_L._Kielland_(platform), all retrieved August 8, 2014.

[2] http://en.wikipedia.org/wiki/Deepwater_Horizon_oil_spill, retrieved August 8, 2014.

[3] http://en.wikipedia.org/wiki/Exxon_Valdez_oil_spill, retrieved August 8, 2014.

[4] See http://www.infoplease.com/ipa/A0001451.html for major oil spills since 1967, and http://news.yahoo.com/s/ac/20110317/sc_ac/8079848_worst_oil_spills_in_history for the five worst oil spills in history. The gravity of disasters can be measured according to economic loss, human loss, and symbolic loss. The July 6, 1988 North Sea off Scotland Occidental Petroleum's Piper Alpha rig disaster killed 167 people, http://en.wikipedia.org/wiki/Piper_Alpha#cite_note-2. The North Sea off Norway March 27, 1980 capsize of the Alexander L. Kielland platform killed 123 people, http://en.wikipedia.org/wiki/Alexander_L._Kielland_(platform), all retrieved August 8, 2014.

from a positive safety effort exerted by the other player. Safety efforts may involve ensuring compliance to, implementing, and developing safety regulations.

The paper develops a general model that is analyzed to provide insights expressed in seven propositions. In stage 1 the government chooses its own safety effort and chooses tax rate to impose on a company. In stage 2 the company chooses safety effort, striking a balance between safety effort and production. The model is solved with backward induction.

Whereas production is routinely analyzed in an economic sense, analyzing a disaster economically is challenging since it may involve loss of human life, uncertain costs of future lawsuits, uncertain costs of countering future lobbying efforts by various groups affected by a disaster, and uncertain reputational ramifications after a disaster. Companies handle this challenge in many different ways. Some may ignore disasters arguing that they are unlikely, that their large profits may pay for disasters, that the government may bail them out, that they may somehow be able to handle disasters ex post, or that bankruptcy is not so bad since individual managers may seek employment elsewhere. Others may rely on safety standards imposed by laws and regulations without economic assessment. Companies employ safety officials working diligently to uphold safety standards, sometimes fighting continuously with other officials seeking to boost production. Different companies have different safety cultures. After a disaster within an industry, or if the CEO has a professed safety focus, or the government have imposed enhanced safety standards, larger budgets may be allocated to safety.

In this paper, disasters are analyzed rationally, in the sense that each player maximizes a quantitative objective function, counteracting the common precariousness, capriciousness, and sometimes irrationality present in many companies' attitudes toward disasters. Companies possess substantial competence to assess production rationally, and adjust production according to changes in demand, changes in other companies' production, and various market uncertainties. However, disasters need to be placed on the same footing as production. Neither the current general public nor future generations are going to accept continuous occurrences of disasters revealing that companies repeatedly fail to approach disasters professionally, fail to use common business sense when assessing disasters, and fail to assess both possible magnitudes and probabilities of disasters.

From an economics perspective, the literature on industrial organization (e.g. Tirole 1988) focuses thoroughly on production but has a limited safety focus. By contrast, the literature on industrial organization from an organizational psychology perspective (e.g. Zohar 1980) focuses on safety, while deemphasizing the role of production. Comparable literature focuses jointly on two purposes. First, Cheung and Zhuang (2012) consider a regulation game between a government who regulates, and competing companies who balance production and safety efforts. Second, Azaiez and Bier (2007) consider the optimal resource allocation for security in reliability systems. Third, Hausken (2006) considers two groups striking a balance between production and contesting each other's production.

Some research has considered disaster preparedness as a partnership game between the government and the private sector, where both players exert safety efforts. For example, Sadka (2007) provides a public economics perspective on public-private partnerships. Flinders (2005) analyzes the role of efficiency, risk, complexity, accountability, and governance in public-private partnerships. Boase (2000) discusses the idea of "governments steering and the private sector rowing," and examines various cases of public-private partnerships. Due to economic externalities, a "free-riding" problem exists on multiple players' security investment as studied by Kunreuther and Heal (2003) and Hausken (2006). Kunreuther and Useem (2010) consider strategies for reaction and response when learning from catastrophes.

Kunreuther (2008) considers reducing losses from catastrophic risks through long-term insurance and mitigation.

This paper is intended to fill an important gap in the literature by placing production and disaster preparedness on the same footing, weighing them against each other, assessing both rationally, and studying the impact on free riding and profits between a company and the government. To our best knowledge, no previous research considers the important tradeoff for each player between production and disaster preparedness, in a game between a company and the government. One exception is Hausken and Zhuang (2013), who consider a stylized model with specific functional forms but do not study the general relationships. The current paper provides such general relationships expressed in seven propositions with conditions and assumptions adjusted for maximum generality. Furthermore, Hausken and Zhuang (2013) assume that the tax rate is chosen in stage 1 and government and company choose safety efforts simultaneously in stage 2, which differs from the sequence of moves of this paper.

In contrast to e.g. Hausken and Zhuang (2013), the model in this paper is analyzed generally without applying specific functional forms. The seven propositions thus provide general analytical insight about which factors impact which factors. We thus sacrifice numerical examples and graphs in order to provide general results.

Boyer and Laffont (1999) present an incomplete contract approach of a political economy of environmental policy and accident prevention using motivational stories similar to those in the present paper. They show why constitutional constraints on the instruments of environmental policy instruments can be preferable, justified by the limitations they impose on politicians' ability to distribute rents.

Regarding the business incentives for investing in safety, see Asche and Aven (2004). They observe that decision-makers do not necessarily communicate about safety in economic terms, and show how safety measures can have a value in an economic sense. England (1988) presents a profit maximization model by a firm utilizing a disaster-prone technology. Output rate and accident prevention are shown to be jointly determined by market demand, production cost and prospective accident loss data. He argues that, in the absence of government safety regulations, even a risk-neutral management is likely to choose an excessively high probability of a Bhopal-style disaster. Golbe (1986) uses data from the US airline industry and finds that the sign of the relationship between profit and safety is indeterminate and depends on risk preferences and the structure of costs and demands. Carmichael (1986) shows that for a competitive labor market with complete information, safety will be underprovided, and that in some cases government-enforced workmen's compensation can bring safety improvements. Hale (2003) considers safety management in production focusing on organizational culture and learning.

In related research Zhuang and Bier (2007) and Hausken et al. (2009) abstract away from production and consider how defenders of infrastructures optimally allocate resources between terrorism, natural disaster, and all hazards. They find that when all-hazards protection is sufficiently cheaper compared with protection against natural disaster only, or terrorism only, it jointly protects against both the natural disaster and terrorism. As the cost increases, all-hazards protection is replaced with either pure natural disaster protection or pure terrorism protection. Osmundsen et al. (2010) do not consider disasters but evaluate in economic terms oil producers' incentives to assure steady supply, which means accounting for various risks that may occur. When steady supply is not assured, reputational issues emerge and contract obligations may be compromised.

A rational approach has benefits but may also cause dilemmas. For example, Ford Motor Corp. famously got in a lot of trouble when it was discovered they were "trading off" safety considerations with profitability (Birsch and Fielder 1994). Any purely optimization approach will make such tradeoffs either explicitly (by weighting safety and performance) or implicitly (with multi-objective optimization, leaving it to the decision-makers to weight safety and performance). For life-threatening disasters, this means putting a price on life, usually handled by considering "the value of a statistical life" (Viscusi 1993). Despite such dilemmas, we believe that the value of transparent elucidation of tradeoffs between safety and production outweighs the disadvantages of camouflaging the tradeoffs.

So-called enterprise risk management (ERM) has emerged to address advanced risk issues, exemplified by guest editorials by Wu and Olson (2009) and Wu et al. (2011a, b) in three special issues. COSO[5] defines ERM as "a process, effected by an entity's board of directors, management and other personnel, applied in strategy setting and across the ... risk to be within its risk appetite." Wu and Olson (2009) defines ERM as "the integrated process of identification, analysis and either acceptance or mitigation of uncertainty in investment decision making..." They argue that "the use of technology for loss-prevention in natural disasters and accidents, and quantitative models to assess derivative risk in insurance and finance, have expanded substantially in the past decade..." Furthermore, they claim that "ERM advocates that taking an integrated approach to risk management in organizations is the most effective way for firms to manage their risks," and that "ERM is a systematic, integrated approach to managing all risks facing an organization." Blome and Schoenherr (2011) analyze supply chain risk management in financial crises in a "research framework" that "rests on the definition of risk management provided by Wu and Olson (2009)." The approach in this paper is general enough to encompass both these two definitions of risk.

Section 2 presents the model. Section 3 analyzes the model. Section 4 concludes. Appendix proves Propositions 1–7.

2 The Model

Companies and governments are subject to laws and regulations regarding safety compliance. Nevertheless, substantial leeway exists for strategic behavior related to profit maximization versus safety investments. We consider a company and a government which are two independent players. The company has a resource R (e.g. a capital good, or labor) which can be converted with unit conversion cost A into productive effort E, and with unit cost B into safety effort S, where

$$R = AE + BS \quad \Leftrightarrow \quad E = (R - BS)/A \quad \Leftrightarrow \quad S = (R - AE)/B \tag{1}$$

The production function is $H(E)$, expressed as $H(S)$ using (1), where $H(E = 0) = 0$. We interpret S as the company's strategic decision variable and assume $\frac{\partial H}{\partial S} < 0$ so that production decreases in safety effort. The disaster probability is thus a contest (Skaperdas 1996, Tullock 1980) between the disaster on the one hand and the two safety efforts on the other hand.

The disaster probability is $p(D, S, s) \geq 0$ where D is the disaster magnitude, and s is the government's safety effort which consists of designing, implanting, and enforcing laws and procedures to ensure safety compliances, as well as organizing drills, creating and maintaining critical infrastructure, and providing grants to the private sector for disaster mitigation and preparedness. All these efforts are observed by the company before choosing S. We assume

5 http://www.coso.org/documents/COSOBoardsERM4pager-FINALRELEASEVERSION82409_001.pdf, retrieved August 8, 2014.

$\frac{\partial p}{\partial D} \geq 0$, $\frac{\partial p}{\partial S} \leq 0$, and $\frac{\partial p}{\partial s} \leq 0$ so that the disaster probability increases in the disaster magnitude and decreases in both safety efforts.

Whereas S and s are intentionally chosen strategic decision variables, and $D \geq 0$ is a variable chosen by nature that represents the perceived natural or technological effort or potential causing disasters. Various methods are used to measure disaster magnitude. Hurricanes are measured in categories 1, 2, 3, 4, 5, etc. Earthquakes are measured on the Richter's scale. Storms are measured by wind speed. Floods are measured by how much the water rises. Explosions are measured in the amount of energy released.

The company's profit is

$$U(S, s, \tau) = (1 - \tau)H(S) - F(D, S, s)p(D, S, s) \tag{2}$$

where τ, $0 \leq \tau \leq 1$, is a taxation percentage variable chosen by the government, and thus the company keeps the fraction $1 - \tau$ after having paid taxes. $F(D, S, s) \geq 0$ is a bounded function which scales the extent to which the company is negatively affected by the disaster.[6] We assume $\frac{\partial F}{\partial D} \geq 0$, $\frac{\partial F}{\partial S} \leq 0$, and $\frac{\partial F}{\partial s} \leq 0$ so that the negative impact on the company increases with the disaster magnitude and decreases in both safety efforts.

The government's profit is

$$u(S, s, \tau) = \tau H(S) - f(D, S, s)p(D, S, s) - bs \tag{3}$$

where $f(D, S, s) \geq 0$ is a bounded function which scales the extent to which the government is negatively affected by the disaster, and b is the government's unit safety effort. We assume $\frac{\partial f}{\partial D} \geq 0$, $\frac{\partial f}{\partial S} \leq 0$, and $\frac{\partial f}{\partial s} \leq 0$ so that the negative impact on the government increases with the disaster magnitude and decreases in both safety efforts. We summarize our assumptions so far as follows:

Assumption 1 $\frac{\partial H}{\partial S} < 0$, $\frac{\partial p}{\partial S} \leq 0$, $\frac{\partial p}{\partial s} \leq 0$, $\frac{\partial F}{\partial D} \geq 0$, $\frac{\partial F}{\partial S} \leq 0$, $\frac{\partial F}{\partial s} \leq 0$, $\frac{\partial f}{\partial D} \geq 0$, $\frac{\partial f}{\partial S} \leq 0$, and $\frac{\partial f}{\partial s} \leq 0$.

We consider a two-stage game where the government chooses the optimal tax rate τ and the optimal safety effort s in stage 1. In stage 2, the company chooses the optimal safety effort S which according to (1) simultaneously determines the optimal productive effort E. This game is equivalent to a three-stage game where the government chooses the optimal tax rate τ in stage 1 and the optimal safety effort s in stage 2, or vice versa, or τ and s simultaneously, and then the company chooses the optimal safety effort S in stage 3.

3 Analyzing the Model

Solving with backward induction, we first solve stage 2 as follows:

Definition 1 A strategy pair (s, τ, S) is a subgame-perfect *Nash Equilibrium* if and only if

$$S = S(s, \tau) = \arg\max_{S \geq 0} U(s, S, \tau), \quad (s, \tau) = \arg\max_{s \geq 0, \tau \geq 0} u(s, S(s, \tau), \tau) \tag{4}$$

[6] The scaling function $F(D, S, s)$ may be estimated by extrapolating from past data. Examples of factors impacting the scaling function are lawyer's fees required to keep court cases going to prevent a company from being financially responsible for a disaster, public relations costs to ensure a company's reputation when suffering from a disaster, and various costs to businesses and society of such disasters that impact the company.

The first order conditions for the company in stage 2 are

$$\begin{cases} S > 0 \Leftrightarrow \frac{\partial U(S,s,\tau)}{\partial S} = (1-\tau)\frac{\partial H(S)}{\partial S} - \frac{\partial F(D,S,s)}{\partial S} p(D,S,s) - F(D,S,s)\frac{\partial p(D,S,s)}{\partial S} = 0 \\ S = 0 \Leftrightarrow \frac{\partial U(S,s,\tau)}{\partial S} = (1-\tau)\frac{\partial H(S)}{\partial S} - \frac{\partial F(D,S,s)}{\partial S} p(D,S,s) - F(D,S,s)\frac{\partial p(D,S,s)}{\partial S} < 0 \end{cases} \tag{5}$$

The company's second order condition in stage 2 is

$$\begin{aligned} \frac{\partial^2 U(S,s,\tau)}{\partial S^2} &= (1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - \frac{\partial^2 F(D,S,s)}{\partial S^2} p(D,S,s) \\ &-2\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial S} - F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S^2} \end{aligned} \tag{6}$$

which is satisfied as negative when

Assumption 2 $\frac{\partial^2 p(D,S,s)}{\partial S^2} \geq 0$, $\frac{\partial^2 F(D,S,s)}{\partial S^2} \geq 0$, and $\frac{\partial^2 H(S)}{\partial S^2} \leq 0$.

The last assumption in Assumption 2 expresses concave production common in highly developed economies, e.g. when the ratio of capital to labor is large (Skiba 1978). Solving (5) gives optimal $S(\tau, s)$ which is inserted into (3) to give the government's first stage utility $u(\tau, s)$, i.e.:

$$u(S(\tau,s), s, \tau) = \tau H(S(\tau,s)) - f(D, S(\tau,s), s) p(D, S(\tau,s), s) - bs \tag{7}$$

Differentiating (7) gives the government's first order conditions in stage 1:

$$\begin{cases} \tau > 0 \Leftrightarrow \frac{du(S(\tau,s),s,\tau)}{d\tau} = H(S(\tau,s)) + \tau\frac{\partial H(S(\tau,s))}{\partial S}\frac{\partial S}{\partial \tau} \\ \quad -\frac{\partial f(D,S(\tau,s),s)}{\partial S}\frac{\partial S}{\partial \tau} p(D,S(\tau,s),s) - f(D,S(\tau,s),s)\frac{\partial p(D,S(\tau,s),s)}{\partial S}\frac{\partial S}{\partial \tau} = 0 \\ \tau = 0 \Leftrightarrow \frac{du(S(\tau,s),s,\tau)}{d\tau} < 0 \end{cases} \tag{8}$$

$$\begin{cases} s > 0 \Leftrightarrow \frac{du(S(\tau,s),s,\tau)}{ds} = \tau\frac{\partial H(S(\tau,s))}{\partial S}\frac{\partial S}{\partial s} - \frac{\partial f(D,S(\tau,s),s)}{\partial s} p(D,S(\tau,s),s) \\ \quad -f(D,S(\tau,s),s)\frac{\partial p(D,S(\tau,s),s)}{\partial s} - f(D,S(\tau,s),s)\frac{\partial p(D,S(\tau,s),s)}{\partial S}\frac{\partial S}{\partial s} - b = 0 \\ s = 0 \Leftrightarrow \frac{du(S(\tau,s),s,\tau)}{ds} < 0 \end{cases} \tag{9}$$

We have determined the Hessian matrix for the government's second order conditions. The matrix covers more than half a page and we prefer not to include it, though it is available upon request. Instead we assume that the second order conditions are satisfied.

Proposition 1 $\lim_{s\to\infty}\frac{dS}{ds} = 0$ *and* $\lim_{S\to\infty}\frac{ds}{dS} = 0$.

The company's budget constraint $S \leq R/B$ implies that $S \to \infty$ requires $R/B \to \infty$. Proposition 1 states that as the safety effort of one player approaches infinity, the change in the other player's safety effort with respect to the first player's safety effort approaches zero. Therefore, the other player's safety effort approaches a constant which may be zero or positive.

Proposition 2 $\lim_{s\to\infty} p(D,S,s) = p_s \geq 0$, $\lim_{S\to\infty} p(D,S,s) = p_S \geq 0$, $\lim_{s\to\infty} f(D,S,s) = f_s \geq 0$, $\lim_{S\to\infty} f(D,S,s) = f_S \geq 0$, $\lim_{s\to\infty} F(D,S,s) = F_s \geq 0$, $\lim_{S\to\infty} F(D,S,s) = F_S \geq 0$, *where* $p_s, p_S, f_s, f_S, F_s, F_S$ *are constants.*

Proposition 2 states that infinitely large safety effort by any player causes the disaster probability and the negative impact of the disaster to decrease towards a constant.

Proposition 3 $\lim_{S\to\infty} s(S) = 0$ *if* $\lim_{S\to\infty} \frac{\partial p(D,S,s)}{\partial s} = 0$ *and* $\lim_{S\to\infty} \frac{\partial f(D,S,s)}{\partial s} = 0$; *and* $\lim_{s\to\infty} S(s) = 0$ *if* $\lim_{s\to\infty} \frac{\partial p(D,S,s)}{\partial S} = 0$ *and* $\lim_{s\to\infty} \frac{\partial F(D,S,s)}{\partial S} = 0$.

The assumptions for Proposition 3 are stronger than those for Propositions 1 and 2. First we assume that the change in the disaster probability as a result of a change in one player's safety effort is zero provided that the other player's safety effort approaches infinity. Second we assume that the change in how one player is negatively affected by the disaster as a result of this player's change in his safety effort is zero provided that the other player's safety effort approaches infinity. With these assumptions, one player's safety effort approaches zero as the other player's safety effort approaches infinity. This means that the two players' safety efforts are strategic substitutes. In practice safety efforts are often or to some extent strategic substitutes, but not always. For example, sometimes the government may not have access to the company's location, equipment, or competence so even if the government invests infinite safety effort, the disaster may still happen.

For Proposition 4 we interpret $S(\tau, s)$ in stage 2 as a best response function to τ and s chosen by the government in stage 1.

Proposition 4 $\frac{dS}{ds} \le 0$ *and* $\frac{ds}{dS} \le 0$ *if* $\frac{\partial^2 p(D,S,s)}{\partial S \partial s} \ge 0$, $\frac{\partial^2 F(D,S,s)}{\partial S \partial s} \ge 0$, *and* $\frac{\partial^2 f(D,S,s)}{\partial S \partial s} \ge 0$.

The three second order conditions specify that higher safety effort by one player decreases the marginal effectiveness, on decreasing the disaster probability and the negative impact of the disaster, of the other player's safety effort. Proposition 4 states that an increase in one player's safety effort decreases the other player's safety effort. This means that the two players' safety efforts are strategic substitutes. Increasing one player's safety effort induces a free rider effect causing the other player to decrease its safety effort.

Proposition 5 $\frac{dS(\tau)}{d\tau} \ge 0$.

Proposition 5 states that higher tax rate τ causes higher company safety effort S. Taxation can ameliorate companies' incentive to free ride on governments' provision of safety effort.

Proposition 6 $S(\tau = 1, s) = \frac{R}{B}$ *causing H(S) = 0.*

Proposition 6 states that if the government imposes maximum tax rate $\tau = 1$, the company focuses exclusively on safety effort and generates no profit for itself, and thus no profit for the government. Maximum tax rate $\tau = 1$ generally means expropriating the company's entire production, and in our model it additionally means that the company responds with no production. This means that governments usually impose some intermediate tax rate τ to ensure some company safety effort, but usually refrain from too high tax rate.

Maximum tax rate $\tau = 1$ does not generally cause a corner solution for the government's safety effort due to the subtraction of bs in (3). For example, we cannot exclude $\tau = 1$ as optimal for the government since zero profit may be preferable when the damage exceeds the benefit from production. Maximum government profit may occur for intermediate, minimum, or maximum safety effort, dependent on the functional forms. Furthermore, zero tax rate $\tau = 0$ does not generally cause zero safety effort $S = 0$ or $s = 0$ since positive safety can optimally decrease the damage even without tax; i.e. $\tau = 0$.

Proposition 7 [7] *Assume* $F(D,S,s) = F$, $\frac{\partial^2 p(D,S,s)}{\partial S \partial D} \le 0$, $\frac{\partial^2 H(S)}{\partial S^2} = 0$ *and*[8]

$$\frac{\partial^3 p(D,S,s)}{\partial S \partial D^2} \frac{\partial^2 p(D,S,s)}{\partial S^2} + \frac{\partial^3 p(D,S,s)}{\partial S^2 \partial D} \left(\frac{\partial^2 p(D,S,s)}{\partial S \partial D} \right) \ge \left[1 + \frac{\frac{\partial^3 p(D,S,s)}{\partial S^3}}{\frac{\partial^2 p(D,S,s)}{\partial S^2}} \right] \left(\frac{\partial^2 p(D,S,s)}{\partial S \partial D} \right)^2 \tag{10}$$

First, $\frac{d^2 S}{dD^2} \le 0$, *and constants* $D_c \ge 0$ *and* $D_g \ge 0$ *exist such that* $\frac{dS}{dD} \ge 0$ *when* $D < D_c$, $\frac{dS}{dD} \le 0$ *when* $D > D_g$. *Second,* $\lim_{D \to \infty} S(D) = S_D \ge 0$ *where* S_D *is a constant.*

Proposition 7, where F is constant, states that the company's safety effort is inverse U shaped in the disaster magnitude D. That is, S first increases in D to protect against the escalating disaster magnitude. Eventually a maximum is reached where further increase of S is not cost efficiently justified. Thereafter S decreases approaching the constant S_D as the disaster becomes too large.

4 Conclusion

One company and one government are analyzed as independent players as they exert costly safety efforts to mitigate the negative impact of a disaster. The disaster probability is modeled as a contest between the disaster magnitude and the two players' safety efforts. The company allocates a resource between safety effort and production. Focusing exclusively on production gives high profit if the disaster does not strike, but is detrimental if the disaster strikes. Focusing exclusively on the safety effort causes bankruptcy. The government benefits from high production in terms of taxation. We allow the company and government to be differently negatively affected by the disaster. The players have different unit costs of safety effort and the company has a unit production cost.

A general model is developed where the government first chooses safety effort, and chooses tax rate to impose on a company. Thereafter the company chooses safety effort, by striking a balance between safety effort and production. Our analytical results include the following, with various plausible assumptions: First, as the safety effort of one player approaches infinity, the change in the other player's safety effort, with respect to the first player's safety effort, approaches zero. Second, an infinitely large safety effort by any player causes the disaster probability and negative impact of the disaster to decrease towards a constant. Third, the two players' safety efforts are strategic substitutes so that one player's safety effort approaches zero as the other player's safety effort approaches infinity. Fourth, an increase in one player's safety effort decreases the other player's safety effort. This enables the players to free ride on each other's safety efforts. Fifth, higher tax rate causes the company to exert higher safety effort. Sixth, if the government chooses maximum tax rate for the company, the company confines attention only to safety effort, exerts no productive effort, and provides no profit.

[7] Presenting Proposition 7 for general $F(D,S,s)$ is technically possible but requires a much more complicated condition than (10).

[8] A set of sufficient but not necessary conditions for (10) to be satisfied are $\frac{\partial^2 p(D,S,s)}{\partial S^2} \ge 0$, $\frac{\partial^3 p(D,S,s)}{\partial S^3} \le 0$, $\left| \frac{\partial^3 p(D,S,s)}{\partial S^3} \right| \ge \left| \frac{\partial^2 p(D,S,s)}{\partial S^2} \right|$, $\frac{\partial^3 p(D,S,s)}{\partial S \partial D^2} \ge 0$ and $\frac{\partial^3 p(D,S,s)}{\partial S^2 \partial D} \le 0$.

Seventh, the company's safety effort is inverse U shaped in the disaster magnitude. The safety effort first increases in the disaster magnitude to mitigate the increasing threat, reach a maximum, and decrease when no longer cost efficiently justified against an overwhelming disaster.

The two players' safety efforts are in this paper shown to be strategic substitutes which we think is most realistic. Future research may analyze special scenarios for example where the government cannot access the company's location, equipment, or competence, or the company does not have the government's abilities, so that the two players' safety efforts to some extent are strategic complements.

The general public can be analyzed as a third player in future research. Also, various special interest groups with diverging preferences can also be analyzed as further players. Such players' safety efforts may consist in making everyone aware of the dangers of various companies' operations, in the form of writing, public demonstrations, etc. In this paper we have assumed that the preferences of such further players are largely aligned with the government's preferences. This holds true in democracies where governments are elected by the public to represent their interests. Furthermore, for example regarding oil production, both prefer safe production and low oil price. However, the preferences of various environmental organizations, various professional groups (fishermen, farmers, etc), sometimes differ from the government's preferences, which can be modeled in future research. The disaster can also be modeled as an adaptive adversary which means analyzing the strategic interaction between a company and the government when facing a strategic threat. Future research may also extend the model to account for heterogeneous risk aversion, moral hazard, and insurance.

Appendix: Proof of Propositions 1–7

Proof of Proposition 1 When $S = 0$, the limit $\lim_{s\to\infty} \frac{dS(s)}{ds}$ is always zero so we only consider $S > 0$. Differentiating the first equation in (5) gives

$$
\begin{aligned}
&\frac{d}{ds}\left(F(D,S,s)\frac{\partial p(D,S,s)}{\partial S}\right) = \frac{d}{ds}\left((1-\tau)\frac{\partial H(S)}{\partial S} - \frac{\partial F(D,S,s)}{\partial S}p(D,S,s)\right)\\
&= -\frac{d}{ds}\left(\frac{\partial F(D,S,s)}{\partial S}p(D,S,s)\right)\\
&\Rightarrow \frac{d}{ds}\left(F(D,S,s)\frac{\partial p(D,S,s)}{\partial S}\right) + \frac{d}{ds}\left(\frac{\partial F(D,S,s)}{\partial S}p(D,S,s)\right) = 0\\
&\Rightarrow \frac{d}{ds}(F(D,S,s))\frac{\partial p(D,S,s)}{\partial S} + \frac{d}{ds}\left(\frac{\partial p(D,S,s)}{\partial S}\right)F(D,S,s)\\
&+\frac{d}{ds}\left(\frac{\partial F(D,S,s)}{\partial S}\right)p(D,S,s) + \frac{d}{ds}(p(D,S,s))\frac{\partial F(D,S,s)}{\partial S} = 0\\
&\Rightarrow \left[\frac{\partial F(D,S,s)}{\partial s} + \frac{\partial F(D,S,s)}{\partial S}\frac{dS}{ds}\right]\frac{\partial p(D,S,s)}{\partial S}\\
&+\left[\frac{\partial^2 p(D,S,s)}{\partial S\partial s} + \frac{\partial^2 p(D,S,s)}{\partial^2 S}\frac{dS}{ds}\right]F(D,S,s)\\
&+\left[\frac{\partial^2 F(D,S,s)}{\partial S\partial s} + \frac{\partial^2 F(D,S,s)}{\partial S^2}\frac{dS}{ds}\right]p(D,S,s)
\end{aligned}
$$

$$
\begin{aligned}
&+\left[\frac{\partial p(D,S,s)}{\partial s}+\frac{\partial p(D,S,s)}{\partial S}\frac{dS}{ds}\right]\frac{\partial F(D,S,s)}{\partial S}=0 \qquad (11)\\
&\Rightarrow \frac{\partial p(D,S,s)}{\partial S}\frac{\partial F(D,S,s)}{\partial s}+\frac{\partial p(D,S,s)}{\partial S}\frac{\partial F(D,S,s)}{\partial S}\frac{dS}{ds}\\
&+F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S\partial s}\\
&+F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S^2}\frac{dS}{ds}+p(D,S,s)\frac{\partial^2 F(D,S,s)}{\partial S\partial s}\\
&+p(D,S,s)\frac{\partial^2 F(D,S,s)}{\partial S^2}\frac{dS}{ds}\\
&+\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial s}+\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial S}\frac{dS}{ds}=0\\
&\Rightarrow \frac{dS}{ds}=\\
&-\frac{\frac{\partial p(D,S,s)}{\partial S}\frac{\partial F(D,S,s)}{\partial s}+F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S\partial s}+p(D,S,s)\frac{\partial^2 F(D,S,s)}{\partial S\partial s}+\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial s}}{\frac{\partial p(D,S,s)}{\partial S}\frac{\partial F(D,S,s)}{\partial S}+F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S^2}+p(D,S,s)\frac{\partial^2 F(D,S,s)}{\partial S^2}+\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial S}}
\end{aligned}
$$

Since p and F are bounded and monotonic in s it follows that $\lim_{s\to\infty}\frac{\partial p(D,S,s)}{\partial s}=0$ and $\lim_{s\to\infty}\frac{\partial F(D,S,s)}{\partial s}=0$, and thus $\lim_{s\to\infty}\frac{\partial^2 p(D,S,s)}{\partial S\partial s}=0$ and $\lim_{s\to\infty}\frac{\partial^2 F(D,S,s)}{\partial S\partial s}=0$. Hence (11) implies $\lim_{s\to\infty}\frac{dS}{ds}=0$. Although s is determined before S, in an overall sense the players are interested in $\lim_{S\to\infty}\frac{ds}{dS}=0$. In contrast to (9) we thus consider the government's first order condition

$$
\begin{cases}
s>0\Leftrightarrow \frac{\partial u(S,s,\tau)}{\partial s}=-\frac{\partial f(D,S,s)}{\partial s}p(D,S,s)-f(D,S,s)\frac{\partial p(D,S,s)}{\partial s}-b=0\\
s=0\Leftrightarrow \frac{\partial u(S,s,\tau)}{\partial s}=-\frac{\partial f(D,S,s)}{\partial s}p(D,S,s)-f(D,S,s)\frac{\partial p(D,S,s)}{\partial s}-b<0
\end{cases}
\qquad (12)
$$

which is analogous to (5) for the company. Hence analogously, $\lim_{S\to\infty}\frac{ds}{dS}=0$. □

Proof of Proposition 2 Follows since $\frac{\partial p}{\partial s}\le 0$,$\frac{\partial p}{\partial S}\le 0$, $\frac{\partial f}{\partial s}\le 0$, $\frac{\partial f}{\partial S}\le 0$, $\frac{\partial F}{\partial s}\le 0$, $\frac{\partial F}{\partial S}\le 0$ as stated in Assumption 1, and since p, f, F have lower bounds 0. □

Proof of Proposition 3 Inserting $\lim_{S\to\infty}\frac{\partial p(D,S,s)}{\partial s}=0$ and $\lim_{S\to\infty}\frac{\partial f(D,S,s)}{\partial s}=0$ into (12) implies $s=0\Leftrightarrow 0>-b$. Inserting $\lim_{s\to\infty}\frac{\partial p(D,S,s)}{\partial S}=0$ and $\lim_{s\to\infty}\frac{\partial F(D,S,s)}{\partial S}=0$ into the second equation in (5) implies $S=0\Leftrightarrow 0>(1-\tau)\frac{\partial H(S)}{\partial S}$. □

Proof of Proposition 4 When $S=0$, $\frac{dS(s)}{ds}$ is always zero so we only consider $S>0$. Similar to the proof of Proposition 1, we have

$$
\frac{dS}{ds}= \qquad (13)
$$
$$
-\frac{\frac{\partial p(D,S,s)}{\partial S}\frac{\partial F(D,S,s)}{\partial s}+F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S\partial s}+p(D,S,s)\frac{\partial^2 F(D,S,s)}{\partial S\partial s}+\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial s}}{\frac{\partial p(D,S,s)}{\partial S}\frac{\partial F(D,S,s)}{\partial S}+F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S^2}+p(D,S,s)\frac{\partial^2 F(D,S,s)}{\partial S^2}+\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial S}}
$$

Since we assume $\frac{\partial p}{\partial S}\le 0,\frac{\partial p}{\partial s}\le 0$, $\frac{\partial F}{\partial S}\le 0$, $\frac{\partial F}{\partial s}\le 0$, $\frac{\partial^2 p}{\partial S^2}\ge 0$, and $\frac{\partial^2 F}{\partial S^2}\ge 0$, the denominator of (13) is always positive. So we have $\frac{dS}{ds}\le 0$ if and only if the numerator of

(13) is positive. One sufficient condition to ensure this is: $\frac{\partial^2 p(D,S,s)}{\partial S \partial s} \geq 0$ and $\frac{\partial^2 F(D,S,s)}{\partial S \partial s} \geq 0$. In summary we have shown $\frac{dS}{ds} \leq 0$ if $\frac{\partial^2 p(D,S,s)}{\partial S \partial s} \geq 0$ and $\frac{\partial^2 F(D,S,s)}{\partial S \partial s} \geq 0$. Analogously, similar to the proof of Proposition 1 and using the first order condition (11), we can show $\frac{ds}{dS} \leq 0$ if $\frac{\partial^2 p(D,S,s)}{\partial S \partial s} \geq 0$ and $\frac{\partial^2 f(D,S,s)}{\partial S \partial s} \geq 0$.

Proof of Proposition 5 When $S = 0$, $\frac{dS(\tau)}{d\tau} = 0$ so we only consider $S > 0$. Differentiating the first equation in (5) gives

$$\frac{d}{d\tau}\left(F(D,S,s)\frac{\partial p(D,S,s)}{\partial S}\right) = \frac{d}{d\tau}\left((1-\tau)\frac{\partial H(S)}{\partial S} - \frac{\partial F(D,S,s)}{\partial S}p(D,S,s)\right)$$

$$\Rightarrow \frac{\partial}{\partial S}\left(F(D,S,s)\frac{\partial p(D,S,s)}{\partial S}\right)\frac{dS}{d\tau} = -\frac{\partial H(S)}{\partial S} + (1-\tau)\frac{\partial^2 H(S)}{\partial S^2}\frac{dS}{d\tau} \tag{14}$$

$$-\frac{\partial}{\partial S}\left(\frac{\partial F(D,S,s)}{\partial S}p(D,S,s)\right)\frac{dS}{d\tau}$$

$$\Rightarrow \frac{dS}{d\tau} = \frac{\frac{\partial H(S)}{\partial S}}{(1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - \frac{\partial}{\partial S}\left(\frac{\partial F(D,S,s)}{\partial S}p(D,S,s)\right) - \frac{\partial}{\partial S}\left(F(D,S,s)\frac{\partial p(D,S,s)}{\partial S}\right)}$$

$$= \frac{\frac{\partial H(S)}{\partial S}}{(1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - \frac{\partial^2 F(D,S,s)}{\partial S^2}p(D,S,s) - 2\frac{\partial F(D,S,s)}{\partial S}\frac{\partial p(D,S,s)}{\partial S} - F(D,S,s)\frac{\partial^2 p(D,S,s)}{\partial S^2}}$$

Because of $\frac{\partial H}{\partial S} < 0$, $\frac{\partial F}{\partial S} \leq 0$, $\frac{\partial^2 p(D,S,s)}{\partial^2 S} \geq 0$, $\frac{\partial^2 F(D,S,s)}{\partial S^2} \geq 0$, and $\frac{\partial^2 H(S)}{\partial S^2} \leq 0$ as stated in Assumptions 1 and 2, we have $\frac{dS(\tau)}{d\tau} \geq 0$. □

Proof of Proposition 6 Inserting tax rate $\tau = 1$ into (2) gives $U(S, s, \tau = 1) = -F(D,S,s)p(D,S,s)$. Since we assume $\frac{\partial p}{\partial s} \leq 0$ and $\frac{\partial F}{\partial S} \leq 0$ in Assumption 1, S needs to be maximum to maximize U. Hence from (1) we have $S(\tau = 1, s) = \frac{R}{B}$. □

Proof of Proposition 7 When $S = 0$, $\frac{dS}{dD} = \frac{d^2 S}{dD^2} = 0$ is always zero so we only consider $S > 0$. From the first equation in (5) we have

$$F\frac{\partial p(D,S,s)}{\partial S} = (1-\tau)\frac{\partial H(S)}{\partial S} \Rightarrow$$

$$\frac{d}{dD}\left(F\frac{\partial p(D,S,s)}{\partial S}\right) = F\frac{\partial^2 p(D,S,s)}{\partial S \partial D} + F\frac{\partial^2 p(D,S,s)}{\partial S^2}\frac{dS}{dD} = \frac{d}{dD}\left((1-\tau)\frac{\partial H(S)}{\partial S}\right)$$

$$= (1-\tau)\frac{\partial^2 H(S)}{\partial S^2}\frac{dS}{dD}$$

$$\Rightarrow \frac{dS}{dD} = \frac{F\frac{\partial^2 p(D,S,s)}{\partial S \partial D}}{(1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - F\frac{\partial^2 p(D,S,s)}{\partial S^2}} \tag{15}$$

where $H(S)$ does not depend on D according to (1). Since we assume $\frac{\partial^2 p(D,S,s)}{\partial S^2} \geq 0$ and $\frac{\partial^2 H(S)}{\partial S^2} \leq 0$ in Assumption 2 and $F \geq 0$ in (2), we have $\frac{dS}{dD} \geq 0$ if and only if $\frac{\partial^2 p(D,S,s)}{\partial S \partial D} \leq 0$.

From (15) we have

$$\frac{d^2 S}{dD^2} = \frac{d}{dD}\left(\frac{F\frac{\partial^2 p(D,S,s)}{\partial S \partial D}}{(1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - F\frac{\partial^2 p(D,S,s)}{\partial S^2}}\right)$$

$$= \frac{\left(F\frac{\partial^3 p(D,S,s)}{\partial S \partial D^2} + F\frac{\partial^2 p(D,S,s)}{\partial S \partial D}\frac{dS}{dD}\right)\left((1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - F\frac{\partial^2 p(D,S,s)}{\partial S^2}\right) + \left(F\frac{\partial^2 p(D,S,s)}{\partial S \partial D}\right)\left((1-\tau)\frac{\partial^3 H(S)}{\partial S^3}\frac{dS}{dD} - F\frac{\partial^3 p(D,S,s)}{\partial S^3}\frac{dS}{dD} - F\frac{\partial^3 p(D,S,s)}{\partial S^2 \partial D}\right)}{\left((1-\tau)\frac{\partial^2 H(S)}{\partial S^2} - F\frac{\partial^2 p(D,S,s)}{\partial S^2}\right)^2} \tag{16}$$

For the special case $\frac{\partial^2 H(S)}{\partial S^2} = 0$ (linear production), (15) and (16) become

$$\frac{dS}{dD} = -\frac{\frac{\partial^2 p(D,S,s)}{\partial S \partial D}}{\frac{\partial^2 p(D,S,s)}{\partial S^2}} \tag{17}$$

$$\frac{d^2 S}{dD^2} = -\frac{\left(\frac{\partial^3 p(D,S,s)}{\partial S \partial D^2} + \frac{\partial^2 p(D,S,s)}{\partial S \partial D}\frac{dS}{dD}\right)\left(\frac{\partial^2 p(D,S,s)}{\partial S^2}\right) + \left(\frac{\partial^2 p(D,S,s)}{\partial S \partial D}\right)\left(\frac{\partial^3 p(D,S,s)}{\partial S^3}\frac{dS}{dD} + \frac{\partial^3 p(D,S,s)}{\partial S^2 \partial D}\right)}{\left(\frac{\partial^2 p(D,S,s)}{\partial S^2}\right)^2} \tag{18}$$

Substituting (17) into (18), we have

$$\frac{d^2 S}{dD^2} = -\frac{\frac{\partial^3 p(D,S,s)}{\partial S \partial D^2}\frac{\partial^2 p(D,S,s)}{\partial S^2} - \left(\frac{\partial^2 p(D,S,s)}{\partial S \partial D}\right)^2 - \frac{\partial^3 p(D,S,s)}{\partial S^3}\frac{\left(\frac{\partial^2 p(D,S,s)}{\partial S \partial D}\right)^2}{\frac{\partial^2 p(D,S,s)}{\partial S^2}} + \frac{\partial^3 p(D,S,s)}{\partial S^2 \partial D}\left(\frac{\partial^2 p(D,S,s)}{\partial S \partial D}\right)}{\left(\frac{\partial^2 p(D,S,s)}{\partial S^2}\right)^2} \tag{19}$$

So we have $\frac{d^2 S}{dD^2} \leq 0$ if and only if (10) is satisfied. For the second part, when D goes to infinity, we must have $\frac{dS}{dD} \leq 0$. Since S must be non-negative, the limit exists. □

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