DECISION ANALYSIS
Vol. 9, No. 2, June 2012, pp. 156–164
ISSN 1545-8490 (print) | ISSN 1545-8504 (online)
http://dx.doi.org/10.1287/deca.1120.0233

Regulation Games Between Government and Competing Companies: Oil Spills and Other Disasters

May Cheung, Jun Zhuang
Department of Industrial and Systems Engineering, University at Buffalo, Buffalo, New York 14260
{mgcheung@buffalo.edu, jzhuang@buffalo.edu}

Oil spills are a characteristic risk of oil drilling and production. There are safety regulations set to reduce the risk of technological failures and human error. It is the oil company's decision to follow such laws and the government's decision to enforce them. Companies are balancing between safety efforts and production competition with other companies. To our knowledge, no previous research has considered the impact of competition in a government–company regulatory game. This paper fills the gap by modeling and comparing two games: a one-company game without competition and a two-company game with competition, both with the government as a regulator. The objectives of all players are to maximize their expected revenue and minimize their losses. Our results indicate that competition increases a company's threshold for risk and therefore requires stricter government regulation. These results could be generalized and applied to other industries including airline, nuclear power, and coal mining.

Key words: game theory; pure and mixed strategies; regulation; competition between companies; oil spill; airline industry; nuclear power; coal mining; disaster; risk
History: Received on May 31, 2011. Accepted on January 11, 2012, after 2 revisions. Published online in *Articles in Advance* April 6, 2012.

1. Introduction

The Deepwater Horizon rig explosion (also known as the British Petroleum (BP) oil spill) in April 2010 killed 11 workers and spilled 4.9 million barrels of oil in the Gulf of Mexico, by far the largest oil spill in history (BBC News 2010). Two key factors leading to this disaster were the company prioritizing production over safety preparedness and a lack of regulation from the government (*The Economist* 2010). In such high-risk, low-probability situations, underevaluation of the risk of disaster undermines the value of preparation (Becker 2010). A company's priority is to stay profitable, and there is very little incentive to take costly preventive measures toward a low-probability event (Posner 2010), including both adaptive and nonadaptive threats. Game theory has been used to study the interaction between government and adaptive threats such as terrorists (Zhuang and Bier 2007, Hausken and Zhuang 2011). Although the occurrence of oil spills is a nonadaptive technological risk, it is still indirectly affected by the strictness of governmental regulations and the cooperation of oil companies (Cohen 1987, Yeager 1990).

Regulation is an important factor, and therefore a highly researched area. For example, Cohen (1987) analyzed the effectiveness of different types of regulation, including incentive systems (Kambhu 1990, Lin 2004), cost observation (Laffont and Tirole 1986), surveillance (Oh 1995), liability (Shavell 1984), and fines (Polinsky and Shavell 1979, Kadambe and Segerson 1998). To more effectively regulate, possible factors that motivate an entity to take risk and disregard regulation must also be analyzed. Specifically, to strengthen safety preparedness in oil operations, factors such as competition need to be studied.

Competition between companies could motivate each company to decrease their level of safety preparedness, focusing more on production in attempts to gain a competitive edge. To our knowledge, no previous paper has studied the impact of competition on a regulation game, which we define as the strategic interaction between the regulator and regulated entities through the medium of laws and rules.

This paper fills the gap by modeling and comparing two games: a one-company game without competition and a two-company game with competition. In particular, the government and oil companies are modeled as rational players who assess their risk and choose the best strategy to maximize their own utility. The safety regulations (i.e., the laws) are publically known: the government decides whether to spend resources to enforce the regulation, whereas the oil companies decide whether to spend resources to follow the regulation. If they are negligent in conforming with safety regulations, they risk getting shut down if caught. If the government is also negligent, not watching over the companies to ensure safe oil operations, then all parties must risk the consequence of a spill. On the other hand, ignoring safety regulations could save both the company and government money if no spill occurs. There is a trade-off between having protection from future risks at a cost or saving expenses on safety at a risk. This trade-off is further complicated by the competition between companies, which will be studied in this paper.

The next section introduces notation, assumptions, and problem formulation. Section 3 studies the one-company game, presenting the best response for the company and the optimal regulation strategy for the government. Section 4 adds a second company and restudies the game, comparing results with those in §3. Section 5 summarizes the paper, generalizes results with applications to other industries, and provides some future research directions. The appendix provides proofs on all theorems stated.

2. Notation, Assumptions, and Problem Formulation

The parameters of our model are defined as follows:

- g: the probability the government assigns to checking a company (companies);
- $y(z)$: the probability company Y (Z) assigns to following regulations;
- p: the probability of an oil spill;
- c_1: the cost to follow the safety regulations (to satisfy requirements, companies must properly train employees, run routine inspections, and maintain equipment updates);
- c_2: the cost to shut down operations (if an oil company is caught not following regulations, the government will not allow any more oil exploration or production);
- c_3: the cost of an oil spill (which includes cleanup costs, liabilities, damaged public image, and government fines; this cost affects both the oil companies and the government; the government may eventually get reimbursed by the oil company but in the meantime must cover the costs itself first);
- k: the cost to the government to check an oil company;
- r_0: the revenue received by the company (when there is only one in the market);
- r_1: the revenue received by both companies that follow safety regulations;
- r_2: the revenue received by the company that does not follow (when the competitor follows);
- r_3: the revenue received by the company that follows (when the competitor does not follow);
- r_4: the revenue received by both companies that do not follow;
- L_Y, L_Z, and L_G: the expected loss of company Y, company Z, and the government, respectively;
- R_Y, R_Z: the expected revenue for company Y and company Z, respectively;
- $y^*(g)$, $z^*(g)$: company's best response to the government's checking probability g;
- g^*: the government's optimal checking probability; and
- g_1, g_2, and g_3: specific checking probabilities for the government as defined later in this paper.

2.1. Assumptions

For simplicity, we assume that if the safety laws are followed, there is no risk of spill. In reality, a risk of spill may be present because of natural causes, but we focus on the risk that can be controlled—namely, human errors and technological failures. The probability of a spill p is exogenously given and known by all players. Furthermore, in the event of a spill, all spills are of the same magnitude.

We study a sequential game, one where the oil companies are the second mover. In practice, the oil companies may have the option of observing the government's strictness in enforcing laws (through observing historical data, actions with other companies, etc.). In contrast, it may not be as plausible to assume a situation where the government can observe an oil company's actions without actually checking on it.

The following relationship between costs is assumed: $c_2 > c_1 > pc_3 > 0$. The largest cost is c_2, when an oil company's operations are shut down. The cost c_1 for each company to follow regulation is assumed to be greater than the expected cost of a spill, pc_3. This assumption is necessary for the oil company to have an incentive to take risk, to avoid dealing with trivial problems.

The two oil companies are assumed to have the same company profile, meaning that they have identical resources, levels of oil production, and associated operation costs. They are competing in the same oil market, where the demand is assumed to be constant. If there is only one company, its revenue is constant at r_0 but is affected by its decision to follow regulations. If there is more than one company, they must compete for revenue; the following relationship then applies: $r_0 > r_2 > r_1 > r_4 > r_3$. If both choose to follow regulations, each will have an equal share of r_1. If one chooses not to follow and the government checks, its operations will be shut down, giving its competitor the entire market with a revenue of r_0. If one chooses not to follow and the government does not check, it will have a market advantage and therefore receive the higher share r_2 while the other receives the lower share r_3. If both companies produce at their maximum level, the market will be oversaturated, and individual revenue will drop to r_4.

Each player is assumed to prefer lower cost and higher revenue. Furthermore, each player understands the setup of the game and will choose whichever pure or mixed strategy will maximize its utility at equilibrium. When the players become indifferent between two courses of action (giving equal utilities), they are assumed to choose the safer option (i.e., the government chooses to check and the company chooses to follow). When there are two companies, the government pays k to check each company and is liable for covering the cost of each oil spill (i.e., if there are two spills, the government must cover the costs of both).

Table 1 **Payoff Table for Simultaneous Two-Company Game**

	Company Z	
Company Y	Follow	Not follow
Follow	$r_1 - c_1$ $r_1 - c_1$	$g(-c_2) + (1-g)(r_2 - pc_3)$ $g(r_0 - c_1) + (1-g)(r_3 - c_1)$
Not follow	$g(r_0 - c_1) + (1-g)(r_3 - c_1)$ $g(-c_2) + (1-g)(r_2 - pc_3)$	$g(-c_2) + (1-g)(r_4 - pc_3)$ $g(-c_2) + (1-g)(r_4 - pc_3)$

Notes. Companies Y and Z each have two possible actions: "follow" and "not follow." For each payoff cell, the lower payoff is for Y and the upper payoff is for Z.

2.2. Problem Formulation

The companies' objectives are to maximize their profits, $U_i = R_i - L_i$ $i = Y, Z$, by choosing probabilities y and z, respectively, to follow regulations. The government's objective is to minimize its loss L_G by choosing the probability g to check companies to enforce regulations. These equations are derived from each game tree in Figure 1 through backward induction with respect to each player's expected payoffs:

$$\max \quad U_Y(g,y) = g\big[y(r_0-c_1)+(1-y)(-c_2)\big] + (1-g)\big[y(r_0-c_1)+(1-y)(r_0-pc_3)\big],$$

$$\min \quad L_G(g,y) = gk+(1-g)(1-y)pc_3.$$

If the company chooses to follow regulations (with probability y), it will receive revenue r_0 with cost c_1. If the company chooses to not follow regulations (with probability $1-y$), it will receive cost c_2 with probability g and a revenue r_0 and cost pc_3 with probability $1-g$. If the government chooses to check (with probability g), it will cost k. If the government chooses to not check (with probability $1-g$), it will receive a cost of pc_3 with probability $1-y$.

In the two-company game, the companies play a simultaneous game with each other first and then interact with the government. These outcomes are presented in Table 1.

The objectives for the two-company game are

$$\begin{aligned} \max \quad & U_Y(g,y,z) \\ &= g\big[yz(r_1-c_1)+y(1-z)(r_0-c_1)+(1-y)z(-c_2)\big] \\ &\quad +(1-g)\big[yz(r_1-c_1)+y(1-z)(r_3-c_1)+(1-y) \\ &\quad \cdot z(r_2-pc_3)+(1-y)(1-z)(r_4-pc_3)\big], \end{aligned}$$

$$\begin{aligned}\max\ & U_Z(g,y,z)\\ &= g\big[yz(r_1-c_1)+(1-y)z(r_0-c_1)+y(1-z)(-c_2)\big]\\ &\quad +(1-g)\big[yz(r_1-c_1)+(1-y)z(r_3-c_1)\\ &\quad +y(1-z)(r_2-pc_3)+(1-y)(1-z)(r_4-pc_3)\big],\\ \min\ & L_G(g,y,z)\\ &= g(2k)+(1-g)\big[y(1-z)pc_3+(1-y)zpc_3\\ &\quad +(1-y)(1-z)2pc_3\big].\end{aligned}$$

3. One-Company Game

We first look at a one-company sequential game, where the government moves first and the company moves second, as depicted in Figure 1(a). Company Y has a monopoly on the market and potential revenue is constant at r_0.

Theorem 1. *The best response of company Y to the government in the one-company game is*

$$y^*(g)=\begin{cases}0 & \text{if } g<g_1,\\ 1 & \text{if } g\ge g_1,\end{cases}\quad \text{where } g_1\equiv\frac{c_1-pc_3}{r_0+c_2-pc_3}.$$

Remark 1. The boundary condition at which the company becomes fully deterred from taking any risk, switching from following to not following, is at the government's checking probability g_1. In other words, if the government wants to motivate oil company Y to follow safety regulations, it must check with at least a probability of g_1.

Theorem 2. *The government's optimal regulation probability for the one-company game is*

$$g^*=\begin{cases}0 & \text{if } L_G(0,0)<L_G(g_1,1),\\ 1 & \text{if } L_G(0,0)\ge L_G(g_1,1),\end{cases}$$

where

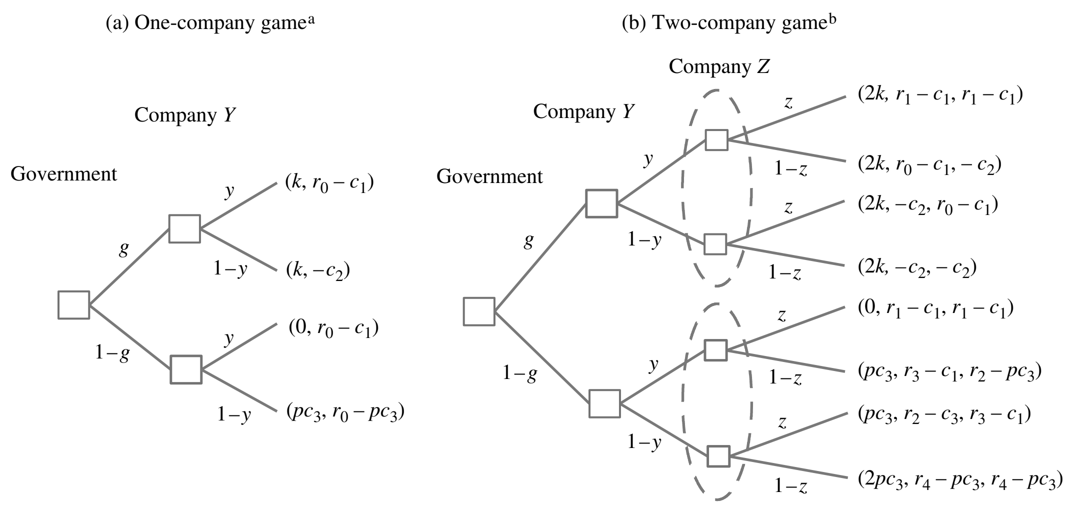
$$g_1\equiv\frac{c_1-pc_3}{r_0+c_2-pc_3}.$$

Remark 2. Theorem 2 states that the two possible regulation probabilities minimizing the government's loss are 0 and g_1. The government should choose not to check at all or to check with a probability of g_1 (the company will react, respectively, with not following and following).

4. Two-Company Game

The addition of a second company, as depicted in Figure 1(b), creates competition in the game. With constant market demand, the two companies now must share the market, lowering their potential revenue. There are four levels of potential revenues, r_1, r_2, r_3, and r_4, which depend on both companies' decisions to follow or not follow safety regulations. In the sequential game, the government moves first and then both companies move together (i.e., both companies play a simultaneous-move game).

Figure 1 **Game Trees**



[a]The two numbers in the parentheses are the utilities of the government and company Y, respectively.
[b]The three numbers in the parentheses are the utilities of the government, company Y, and company Z, respectively.

Theorem 3. *The company Y's and company Z's best response to each other and the government in the two-company sequential game is*

$$y^*(g), z^*(g) = \begin{cases} 0 & \text{if } g < g_2, \\ \dfrac{g(-r_4+r_3-r_0-c_2+pc_3)+r_4-r_3+c_1-pc_3}{g(-r_4+r_3+r_2-r_0)+r_4-r_3-r_2+r_1} & \text{if } g_2 \le g < g_3, \\ 1 & \text{if } g \ge g_3, \end{cases}$$

where

$$g_2 \equiv \frac{r_4-r_3+c_1-pc_3}{r_0+r_4-r_3+c_2-pc_3} \quad \text{and} \quad g_3 \equiv \frac{r_2-r_1+c_1-pc_3}{r_2+c_2-pc_3}.$$

Theorem 4. *The threshold checking probability g^* required to fully deter the oil companies from being negligent in following safety procedures increases from g_1 in the one-company case to g_3 in the two-company case, with an addition of threshold g_2, where the companies start being deterred; that is, $g_1 < g_2 < g_3$.*

Remark 3. Theorem 3 shows that competition has introduced new boundary conditions g_2 and g_3. At boundary condition g_2, the companies switch from using pure strategies (not follow, not follow) to using mixed strategies. At boundary condition g_3, the companies switch from mixed strategies to pure strategies (follow, follow). Theorem 4 supports that competition increases an oil company's willingness to take risks, shifting the boundary conditions up from the one- to the two-company game. In particular, going from panel (a) to panel (b) in Figure 2, the region where the companies play the pure strategy "follow" expands, whereas the region where the companies play the pure strategy "not follow" shrinks.

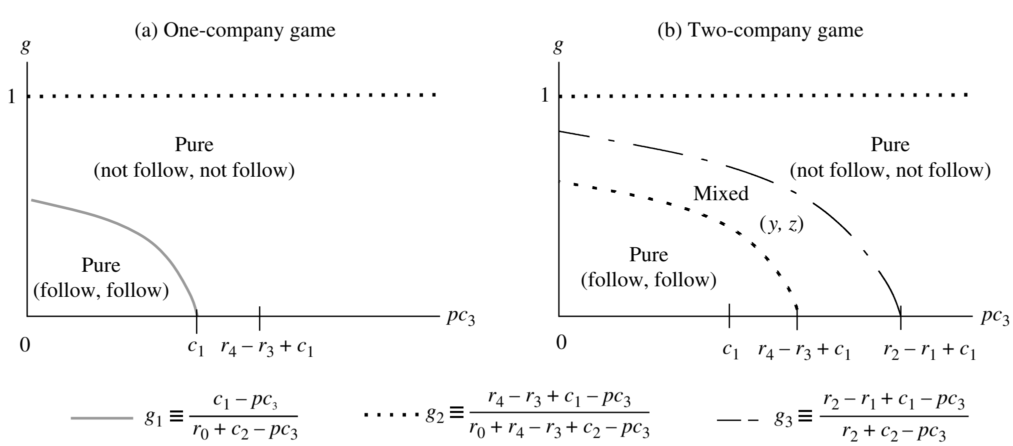
With the addition of competition, the decision to follow safety regulations becomes more complicated; there are more factors to weigh in when an oil company is studying the cost–benefit analysis of taking such a risk. This means that two oil companies in competition have a higher likelihood to disregard safety regulations than one company itself. The implication is that in the real-world oil industry, where there is more than just one rival company, competition is higher, and so is the incentive to cut corners on safety.

Theorem 5. *The government's optimal regulation probability for the two-company game is*

$$g^* = \begin{cases} 0 & \text{if } L_G(0,0,0) < L_G(g_2, y^*(g_2), z^*(g_2)) \\ & \quad \text{and } L_G(0,0,0) < L_G(g_3,1,1), \\ g_2 & \text{if } L_G(g_2, y^*(g_2), z^*(g_2)) < L_G(0,0,0) \\ & \quad \text{and } L_G(g_2, y^*(g_2), z^*(g_2)) < L_G(g_3,1,1), \\ g_3 & \text{if } L_G(g_3,1,1) < L_G(0,0,0) \\ & \quad \text{and } L_G(g_3,1,1) < L_G(g_2, y^*(g_2), z^*(g_2)). \end{cases}$$

Remark 4. Theorem 5 shows that competition among the oil companies has introduced three other

Figure 2 Best Response Comparison



possible optimal checking probabilities: 0, g_2, and g_3. As Theorems 3 and 4 indicate, the companies' risk threshold has increased. Therefore, to maintain the same level of safety from the one-company game to the two-company game, the government must implement a higher checking probability g.

The implication here is that in the real-world oil industry, where there are more than just two oil companies to oversee, a stringent level of regulation is even more necessary. Understanding that competition is a persistent factor and how it affects a company's decision in regard to safety regulations is a key step in preventing another disaster such as the BP oil spill.

5. Conclusion and Extensions

5.1. Summary

In the one-company game, we solved for one company's best response, which included only pure strategies with one boundary condition, and for the government's optimal checking probabilities, which included two. In the two-company game, the companies used both pure and mixed strategies in their best response with three boundary conditions, and the government had three optimal checking probabilities. Our results indicated that the competition introduced by adding a second company shifted the boundary conditions and, therefore, the optimal checking probabilities upward. We conclude that competition effectively increases a company's motivation for risk taking and in turn requires stricter regulation from the government. Understanding that competition affects the willingness of oil companies to comply with safety standards could help the government more effectively regulate and prevent oil disasters, especially when in reality there are more than just two oil companies.

It is interesting to note the counterintuitive observation that competition can have such negative impacts. Competition is well known to be able to help reduce prices for consumers, motivate innovation in companies, and produce lean systems of production (Rosenau 2003). However, our result indicates that, in contrast, competition makes it more difficult for the government to regulate companies, because they become more willing to take on risk (i.e., having an increased risk threshold) to gain a competitive edge in the market.

5.2. Application to Other Industries

In this subsection, we discuss potential applications of our results to other industries including U.S. airlines, U.S. nuclear energy, and coal mining in China. In all the examples provided, increased competition has motivated companies in various industries to find alternative methods to stay profitable. These alternatives have reduced safety levels and increased the risk of disaster.

Since the U.S. airline deregulation in 1979, competitiveness has proven difficult because of the volatile nature of airline profits, which are heavily affected by fuel prices and the attacks on September 11, 2001 (Gowrisankaran 2002). In the two instances discussed below, U.S. airlines seem to be prioritizing profitability over safety in attempts to stay competitive.

One instance is that the U.S. Airport Transportation Association (ATA) sent a letter requesting the U.S. Federal Aviation Administration to reconsider its pilot fatigue regulation (the regulation requires longer rest periods for pilots) (Crawley 2011). In that letter, the ATA concluded that the regulation measure was too costly to comply with, estimating a loss of $2 billion dollars and 27,000 jobs. Another instance is the 2011 court trial where the U.S. Airline Pilots Association sued US Airways for forcing pilots to fly under unsafe conditions (to improve company performance and maintain competitiveness) (Portillo 2011).

When the U.S. electricity utility industry started deregulation during the early 1990s, Edison Electric Institute studied nuclear power's competitive potential against other retail competition (Riccio 1996). This study concluded nuclear power plant operations and maintenance to be expensive. To stay competitive, plants have increased productivity beyond their established capabilities, violating many safety regulations, and in response, the Nuclear Regulatory Commission has weakened safety standards so that aging nuclear reactors can stay in compliance (Donn 2011). These practices have certainly increased the risks of a nuclear meltdown.

In the mid-1990s, coal mining conditions in China's state-owned enterprises (SOEs) stopped improving, keeping fatality rates high (Wright 2004). This is because the rise of township and village enterprises (TVEs) created a competitive environment that depressed wages and conditions. TVEs use cheap labor from China's rural areas, forcing the decline of profits for SOEs. According to Wright (2004), this competitive environment pressures SOEs to cut costs, with safety being largely impacted. Outdated technology continues to be used by inexperience workers, who are often asked to work extra shifts under high-demand production requirements.

In all three aforementioned industries, the difficulties of staying competitive have incentivized companies to cut corners on safety preparedness. The U.S. airline industry is resisting improvements to standards and ordering planes to fly under unsafe conditions, the U.S. nuclear energy industry is pushing aging nuclear plants to operate beyond their limitations, and the Chinese coal mining industry is subjecting inexperience workers to stressful and dangerous environments. In such cases, stricter regulation, in terms of both setting and enforcing laws, is crucial to maintaining a high safety standard and preventing disasters. The absence or corruption of safety regulation will and has led to formidable consequences.

5.3. Future Research Directions

In this paper, we have seen a significant difference in the company's best response and government's optimal strategy when there is an addition of just one other company. An extension to an N-player game would help generalize the conclusions made. There may be further interesting results to be found, such as the effect of competition approaching a limit as more companies are added.

We have studied a sequential game where the oil companies had perfect information about the government's checking probability. Various forms of regulation games with competition could also be studied, including those with imperfect/incomplete information and simultaneous-move games between the government and oil companies.

The assumption of the oil companies having identical resources and utility functions simplifies the players' interactions with each other and the government. In the future, we could study heterogeneous company profiles. In addition, the players were assumed to be risk neutral. To build a more robust model, we would like to allow players to have some risk preferences (i.e., risk seeking, risk averse; see Laffont and Rochet 1996).

Finally, adding a revenue component to the government will give more dynamic interactions between the players. The government also receives royalties from the same companies that they regulate. This conflict of interest was another crucial component causing the BP oil spill (Walsh 2010). We can then study the direct impact of competition on the government. In addition to competition, vertical integration and control issues between the oil companies are other major factors that could be studied.

Acknowledgments

The authors thank the special issue editors and two anonymous referees of *Decision Analysis* for useful comments and suggestions. This research was partially supported by the U.S. Department of Homeland Security through the National Center for Risk and Economic Analysis of Terrorism Events (CREATE) [Award 2010-ST-061-RE0001]. However, any opinions, findings, and conclusions or recommendations in this document are those of the authors and do not necessarily reflect views of the U.S. Department of Homeland Security or CREATE. Jun Zhuang is the corresponding author.

Appendix

Proof to Theorem 1

The government checks with probability g; company Y reacts to the government with probability y. We solve for the optimal checking probability that makes company Y indifferent between its pure strategies follow and not follow. By setting equal their expected payoffs,

$$\text{Expected payoff of following} = g(r_0 - c_1) + (1-g)(r_0 - c_1) = r_0 - c_1,$$

$$\text{Expected payoff of not following} = g(-c_2) + (1-g)(r_0 - pc_3),$$

we get $g_1 = (c_1 - pc_3)/(r_0 + c_2 - pc_3)$. If $g < g_1$, the expected cost of following is greater than not following, and thus $y^* = 0$. Likewise, if $g > g_1$, we have that the expected cost of following is less than that of not following, and thus $y^* = 1$.

Proof to Theorem 2

First, any probability $g \in [0, g_1)$ is dominated by $g^* = 0$ because increasing the checking probability in this region will not change the company's decision according to Theorem 1; it will only increase the cost for the government. The company will always choose to not follow. Second, any probability $g \in [g_1, 1]$ is dominated by $g^* = g_1$ because again increasing the checking probability in this region will not change the company's decision according to Theorem 1; it will only increase the government's cost. The company will always choose to follow. Therefore, there are only two possible optimal checking probabilities: 0 and g_1. The government's objective function for the one-company game is

$$\min L_G = gk + (1-g)(1-y)pc_3.$$

The government will compare the two expected loss outcomes $L_G(0,0) = pc_3$ and $L_G(g_1, 1) = [(c_1 - pc_3)/(r_0 + c_2 - pc_3)]k$, and choose the g^* that will minimize its loss.

Proof to Theorem 3

We solve for the simultaneous game between the companies first, for which then we can define the boundary condition for g. Table 1 is a payoff table for the two companies for their two pure strategies. It is worthy to note that because the company profiles are identical, the payoff table is also symmetric, giving identical equilibriums for companies Y and Z.

• For (not follow, not follow) to be a Nash equilibrium, the expected payoff of playing "not follow" must be greater than the expected payoff of playing "follow":

$$g(-c_2) + (1-g)(r_4 - pc_3) > g(r_0 - c_1) + (1-g)(r_3 - c_1).$$

Solving for g, we get

$$g < g_2 \equiv \frac{r_4 - r_3 + c_1 - pc_3}{r_0 + r_4 - r_3 + c_2 - pc_3}.$$

• For (follow, follow) to be a Nash equilibrium, we must have

$$r_1 - c_1 \geq g(-c_2) + (1-g)(r_2 - pc_3).$$

Solving for g, we get

$$g \geq g_3 \equiv \frac{r_2 - r_1 + c_1 - pc_3}{r_2 + c_2 - pc_3}.$$

• For (follow, not follow) and (not follow, follow) to be Nash equilibria, we must have

$$r_1 - c_1 < g(-c_2) + (1-g)(r_2 - pc_3) \quad \text{and}$$

$$g(-c_2) + (1-g)(r_4 - pc_3) < g(r_0 - c_1) + (1-g)(r_3 - c_1).$$

Solving for g, we get, respectively,

$$g \geq \frac{r_4 - r_3 + c_1 - pc_3}{r_0 + r_4 - r_3 + c_2 - pc_3} \quad \text{and}$$

$$g < \frac{r_2 - r_1 + c_1 - pc_3}{r_2 + c_2 - pc_3}.$$

Simplifying this, we get $g_2 \leq g < g_3$. Because there is no dominant pure strategy for this condition, we assume that both companies use mixed strategies. To find the mixed strategy equilibrium, we look for the $z^*(g)$ and $y^*(g)$ that will make companies Y and Z, respectively, indifferent to their pure strategies:

$$\text{Expected payoff } (Y \text{ follow}) = z(r_1 - c_1) + (1-z)\big[g(r_0 - c_1) + (1-g)(r_3 - c_1)\big],$$

$$\text{Expected payoff } (Y \text{ not follow}) = z\big[g(-c_2) + (1-g)(r_2 - pc_3)\big] + (1-z)\big[g(-c_2) + (1-g)(r_4 - pc_3)\big];$$

$$\text{Expected payoff } (Z \text{ follow}) = y(r_1 - c_1) + (1-y)\big[g(r_0 - c_1) + (1-g)(r_3 - c_1)\big],$$

$$\text{Expected payoff } (Z \text{ not follow}) = y\big[g(-c_2) + (1-g)(r_2 - pc_3)\big] + (1-y)\big[g(-c_2) + (1-g)(r_4 - pc_3)\big].$$

By setting these two payoffs equal and solving, we get

$$y^*(g) = z^*(g) = \frac{g(r_4 - r_3 + r_0 + c_2 - pc_3) - r_4 + r_3 - c_1 + pc_3}{g(r_4 - r_3 - r_2 + r_0) - r_4 + r_3 + r_2 - r_1}.$$

Proof to Theorem 4

The boundary conditions where the companies get deterred from being negligent are g_1 and g_2 for the one- and two-company games, respectively.

We prove below that $g_1 < g_2$ in the following two cases for pc_3 (refer to Table 1):

(1) $0 \leq pc_3 < c_1$. We set $a \equiv c_1 - pc_3 > 0$, $b \equiv c_2 - c_1 + r_0 > 0$, $c = r_4 - r_3 > 0$. After substituting these values into

$$\frac{r_4 - r_3 + c_1 - pc_3}{r_0 + r_4 - r_3 + c_2 - pc_3} < \frac{r_2 - r_1 + c_1 - pc_3}{r_2 + c_2 - pc_3},$$

we get

$$\frac{a}{a+b} < \frac{a+c}{a+b+c},$$

which simplifies to $0 < bc$. This inequality always holds, so $g_1 < g_2$.

(2) $pc_3 \geq c_1$. When $pc_3 = c_1$, $g_1 = 0$ while $g_2 > 0$, so $g_1 < g_2$.

We prove next that $g_2 < g_3$ in the following two cases for pc_3 (refer to Table 1):

(1) $0 \leq pc_3 < r_4 - r_3 + c_1$. We set $a \equiv r_4 - r_3 - pc_3 + c_1 > 0$, $b \equiv c_2 - c_1 + r_0 > 0$, $c \equiv -r_4 + r_3 + r_2 - r_1 > 0$. After substituting these values in

$$\frac{r_4 - r_3 + c_1 - pc_3}{r_0 + r_4 - r_3 + c_2 - pc_3} < \frac{r_2 - r_1 + c_1 - pc_3}{r_2 + c_2 - pc_3},$$

we get

$$\frac{a}{a+b} < \frac{a+c}{a+b+c},$$

which simplifies to $0 < bc$. This inequality always holds, so $g_2 < g_3$.

(2) $pc_3 \geq r_4 - r_3 + c_1$. When $pc_3 = r_4 - r_3 + c_1$, $g_2 = 0$ while $g_3 > 0$, so $g_2 < g_3$.

Combining these two results, we have $g_1 < g_2 < g_3$.

Proof to Theorem 5

Using the same reasoning from the proof to Theorem 2, any $g \in [0, g_2)$ is dominated by $g^* = 0$. The companies will choose (not follow, not follow) in this region. Similarly any $g \in [g_2, g_3)$ is dominated by $g^* = g_2$, where the companies use a mixed strategy. Last, any $g \in [g_3, 1]$ is dominated by $g^* = g_3$, and the companies will choose (follow, follow) in this region. The government objective for the two-company game is represented by

$$\min \quad L_G(g,y,z) = g(2k) + (1-g) \cdot \left[y(1-z)pc_3 + (1-y)zpc_3 + (1-y)(1-z)2pc_3\right],$$

and because $y^*(g) = z^*(g)$, the equations is simplified to

$$\min \quad L_G(g,y,z) = g(2k) + (1-g)(1-y)2pc_3.$$

Comparing the three expected loss outcomes,

$$L_G(0,0,0) = 2pc_3,$$

$$L_G(g_2, y^*(g_2), z^*(g_2)) = g_2(2k) + (1-g_2) \cdot \left(1 - \frac{g(r_4 - r_3 + r_0 + c_2 - pc_3) - r_4 + r_3 - c_1 + pc_3}{g(r_4 - r_3 - r_2 + r_0) - r_4 + r_3 + r_2 - r_1}\right)(2pc_3),$$

$$L_G(g_3, 1, 1) = g_3(2k) + (1-g)(2pc_3),$$

the government will choose the g^* that minimizes its loss.

References

BBC News (2010) Timeline: BP oil spill. (September 19), http://www.bbc.co.uk/news/world-us-canada-10656239.

Becker G (2010) The gulf oil leak and optimal safety precautions. *Beckner-Posner Blog* (July 4), http://www.becker-posner-blog.com/2010/07/the-gulf-oil-leak-and-optimal-safety-precautions-becker.html.

Cohen MA (1987) Optimal enforcement strategy to prevent oil spills: An application of a principal-agent model with "moral hazard." *J. Law Econom.* 30(1):23–51.

Crawley J (2011) US airlines say pilot fatigue rule would cost jobs. *Thomson Reuters* (September 15), http://www.reuters.com/article/2011/09/15/airlines-fatigue-idUSS1E78E1WT20110915.

Donn J (2011) U.S. nuclear regulators weaken safety rules, fail to enforce them: AP investigation. *Huffington Post* (June 20), http://www.huffingtonpost.com/2011/06/20/us-nuclear-regulators-safety-industry_n_880222.html.

Economist, The (2010) The oil well and the damage done. (June 17), http://www.economist.com/node/16381032.

Gowrisankaran G (2002) Competition and regulation in the airline industry. Federal Reserve Bank of San Francisco Economic Letter 2002-01, January 18. Accessed January 5, 2012, http://www.frbsf.org/publications/economics/letter/2002/el2002-01.html.

Hausken K, Zhuang J (2011) Governments' and terrorists' defense and attack in a *T*-period game. *Decision Anal.* 8(1):46–70.

Kadambe S, Segerson K (1998) On the role of fines as an environmental enforcement. *J. Environ. Planning Management* 41(2): 217–226.

Kambhu J (1990) Direct controls and incentives systems of regulation. *J. Environ. Econom. Management* 18(2):72–85.

Laffont J-J, Tirole J (1986) Using cost observation to regulate firms. *J. Political Econom.* 94(3):614–641.

Laffont J-J, Rochest J-C (1996) Regulation of a risk averse firm. *Games Econom. Behav.* 25(2):149–173.

Lin S-W (2004) Designing incentive systems for risk-informed regulation. Ph.D. dissertation, Department of Industrial and Systems Engineering, University of Wisconsin–Madison, Madison.

Oh Y (1995) Surveillance or punishment? A second-best theory of pollution regulation. *Internat. Econom. J.* 9(3):89–101.

Polinsky AM, Shavell S (1979) The optimal tradeoff between the probability and magnitude of fines. *Amer. Econom. Rev.* 69(5): 880–891.

Portillo E (2011) US airways, pilots union spar in court. *Charlotte Observer* (August 19), http://www.charlotteobserver.com/2011/08/19/2540023/us-airways-pilots-union-spar-in.html.

Posner R (2010) The gulf oil leak. *Becker-Posner Blog* (July 4), http://www.becker-posner-blog.com/2010/07/the-gulf-oil-leakposner.html.

Riccio J (1996) Competition and nuclear power: A dangerous combination. *Synthesis/Regeneration Magazine Online* 11 (Fall), http://www.greens.org/s-r/11/11-10.html.

Rosenau PV (2003) *The Competition Paradigm: America's Romance with Conflict, Contest, and Commerce* (Rowman and Littlefield, Lanham, MD).

Shavell S (1984) A model of the optimal use of liability and safety regulation. *RAND J. Econom.* 15(2):271–280.

Walsh B (2010) The Gulf disaster: Whose asses need kicking? *Time Magazine* (June 10), http://www.time.com/time/magazine/article/0,9171,1995843,00.html.

Wright T (2004) The political economy of coal mine disasters in China: "Your rice bowl or your life." *China Quart.* (179):629–646.

Yeager PC (1990) *The Limits of Law: The Public Regulation of Private Pollution* (Cambridge University Press, Cambridge, UK).

Zhuang J, Bier VM (2007) Balancing terrorism and natural disasters—Defensive strategy with endogenous attack effort. *Oper. Res.* 55(5):976–991.