A Model of Endogenous Oil Spill Regulation

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Abstract

This paper presents a model of endogenous oil spill regulation where the severity of regulations is shown to be a function of the size of recent spills. The regulator chooses how much to regulate in order to maximize political capital when regulations are rigid downwards and the distribution of spills is not known with certainty. Very large spills are shown to cause large increases in the regulation level. In the event that an unlikely disastrous spill is realized, major regulatory reform may take place which would take the regulations to too high a level.

1 Introduction

After the discovery of oil-saturated sands in Alaska's North Slope in January 1968, the oil companies, looking for a way to transport the oil, proposed a pipeline. Although Friends of the Earth and fishermen filed suit against the proposed pipeline, seven oil companies formed a consortium, namely Alyeska, and with intensive lobbying succeeded in clearing the way for the Trans-Alaska Pipeline and the tanker route on the condition that no effort to protect the environment would be spared. An explicit oil spill contingency plan, with the names and backgrounds of the clean-up personnel, the equipment that would be available, etc. was prepared. The state of Alaska created the Department of Environmental Conservation (DEC) to ensure that the oil companies kept their promises.

The belief in the high safety standards achieved in the transport system is best expressed by Art Davidson as an Alaskan and an employee for the Friends of the Earth [1]:

When oil started flowing through the pipeline in 1977, my own fears about the project had been somewhat allayed. It is true that the safer, all-overland pipeline route through Canada had been rejected, but the industry, the state of Alaska, and the federal government were all promising the American public the safest pipeline and the tanker system in the world. I remember one very high-ranking British Petroleum official confiding to me that " You environmentalists drove us crazy... but now we have a truly superior oil transport system."

When Exxon Valdez grounded on a submerged reef on March 24^{th}, 1989, in the course of a day 240,000 barrels of oil were in the water. This was the worst oil spill in the history of United States. Yet Exxon was known as the one of the best in tanker maintenance and had a reputation for hiring the best people. The Exxon Valdez was the least likely tanker to have an accident. It was only three years old and had not had any problems with violations or accidents before. Exxon was found "negligent" and fined $1.125 billion in damages. Public outrage towards a catastrophe of this kind brought environmental regulations under attack. Liability limits under the existing regulations were much too low for a spill of this size. It was

[1] Davidson, Art, In the Wake of the Exxon Valdez, San Francisco, 1990, page 10

determined that the captain of the Exxon Valdez was under the influence of alcohol when the accident occurred yet regulations had no control over personnel or tanker standards. What has become to be known as the Oil Pollution Act(OPA) was passed in 1990, greatly modifying the existing oil spill regulations to correct for these inadequacies.

This is typical of how federal, state and international laws regulating oil spills have evolved over the years[2]. Well publicized spills have proven very effective in drawing a quick response from the regulators. The grounding of the Torrey Canyon in 1967 immediately gave rise to new international conventions which later became law. The Santa Barbara oil spill in 1969 was the impetus behind the 1970 amendment to the Federal Water Pollution Act (1948), which added a provision specifically dealing with spills of oil and hazardous substances was added. This paper attempts to model this behavior. In the next section, a review of the literature is provided, followed by a description of a model in which regulators react to catastrophic oil spills by introducing new regulations or making existing regulations stricter. The conclusion highlights the main results.

2 Literature Review

The theoretical literature on oil spill regulation is built on the literature on stochastic pollution. The principal-agent framework has been a commonly-applied tool where the agent is involved in an activity that stochastically pollutes the environment. The agent can take preventive measures that reduce the probability of accidents that may result in pollution.

[2]For a review see the Appendix.

The accident affects the utility of both the agent and the principal. The agent at a minimum incurs the resource loss (private cost), but can be held responsible for some or all of the environmental loss (social cost). The interesting question is to characterize a contract between the two parties that will induce the agent to choose the optimal level of precaution. Examples include works by Sarin and Scherer (Sarin & Scherer 1976), Hartford (Hartford 1987), Beavis and Walker (Beavis & Walker 1983), Epple and Visscher (Epple & Visscher 1984), and Mark Cohen (Cohen 1987). There has been substantial discussion on the use of liability versus regulation for regulating oil spills. Advocates for the use of liability include Bradley (Bradley 1974) and Hartje (Hartje 1984). Shavell (Shavell 1983) argues for minimum regulation.

In this paper, we focus on how regulations evolve. We do not model a regulator that is trying to get the tanker operators to take the optimal level of care, but one that just responds to political pressure. Producers exert pressure for lower regulations, and consumers exert pressure for what they think regulations should be. The model resembles Harris and Holmstrom's (Harris & Holmstrom 1982) model of labor contracts in spirit. In the next section, we describe the model in detail.

3 The Basic Model

In this section, we develop a model where regulators respond to large spills by imposing more stringent regulations. The regulator chooses the level of regulation l to maximize political capital that depends on producers' satisfaction, P, and consumers' satisfaction,

C. Producers' satisfaction is negatively related to the level of regulation, l ($P'(l) < 0$ and $P''(l) < 0$). Consumers' satisfaction is a decreasing function of the gap between the actual level of environmental regulation, l, and the perceived optimal level of regulation, p. The function is maximized at $l = p$ ($C'(0) = 0$), with $C'(l-p) < 0$ for $l-p > 0$ and $C''(l-p) < 0$. Consumers, in this specification, include environmental groups that lobby for environmental regulations.

One spill is observed in every time period. The size of the spill, S, is a random draw from a probability distribution function $f(S;\hat{m})$ where $\hat{m}$ is the true mean spill size. It is common knowledge that i) the true p.d.f. is a member of a class of continuous one-parameter p.d.f.'s; ii) the single parameter can be characterized in terms of the mean; and iii) members of the class can be strictly ordered in terms of first-order stochastic dominance, so that $F(S;m') > F(S;m'')$ for $m'' > m'$. The true mean spill size, $\hat{m}$, is not known, however. The regulator, the consumers and producers all use the same estimate for it which we denote by $m_s = E(m|I(s))$ where m_s is the estimate for m at time s conditional on information available at time s, $I(s)$. $p_s = p(m_s)$ is an increasing function of m_s ($p' > 0$).

We assume that regulations are rigid downwards but that the regulator can increase the level of regulation. The timeline is as follows: l_{t-1} and m_{t-1} are the state variables at the beginning of time t. S_t is observed and the estimate for m_{t-1} is updated to m_t. Then l_t, the regulation level for time t is chosen and implemented. The regulator's problem at time t is to maximize expected political capital over its lifetime, from t until the terminal period, T.

$$\max_{l_s} \quad E_t \sum_{s=t}^{T} \quad \{P(l_s) + C(l_s - p_s)\} \tag{1}$$

$$s.t. \quad l_{s-1} \leq l_s$$

and the stochastic process generating the spills. To simplify the analysis, discounting is ignored. Let $V_t(l_t, m_t) = V_t$ denote a value function that represents the expected lifetime political capital at time t immediately after S_t is observed, when all future decisions are optimal. The regulator's problem in terms of value functions can be written as a two-period problem.

$$V_t = \max_{l_t} P(l_t) + C(l_t - p_t) + E_t V_{t+1} \qquad s.t. \;\; l_t \geq 0, l_t \geq l_{t-1} \tag{2}$$

The regulator would only increase the level of regulation if the consumers desire it so. This would only happen if S_t, and thus m_t and $p(m_t)$ are large compared to the existing level of regulation, l_{t-1}. Let $\bar{S}_t$ be the threshold level of spill in period t above which the regulator deems l_{t-1} to be inadequate given the new estimate of mean spill size and undertakes regulatory reform in that period. Also let $\hat{L}_s(m_s(S))$ for $s > t$ be the optimal regulation level at some future period s conditional on spill S and m_{s-1} with the dependence on m_{s-1} being suppressed. Then we can rewrite the problem as:

$$\begin{aligned} V_t &= \max_{\substack{l_t \\ \bar{S}_{t+1}}} P(l_t) + C(l_t - p_t) + \int_0^{\bar{S}_{t+1}} V_{t+1}(l_t, p(m_{t+1}(S))) f(S; m_t) dS \\ &\quad + \int_{\bar{S}_{t+1}}^{\infty} V_{t+1}(\hat{L}_{t+1}(m_{t+1}(S)), p(m_{t+1}(S))) f(S; m_t) dS \\ s.t. &\quad l_t \geq 0, l_t \geq l_{t-1}, \bar{S}_{t+1} \geq 0 \end{aligned} \tag{3}$$

The choice of l_t depends on the value of m_t which in turn is dependent on S_t. Note that l_t denotes the level of regulation given the realization of S_t in period t. We denote regulations in future periods as functions of the estimate for mean spill size which in turn is a function of the size of spills. For ease of notation, we are going to assume $p(m_t) = m_t$ and , hereafter, we are not going to state the non-negativity constraints on the choice variables. The rule for updating beliefs about m is given by:

$$m_t = \frac{m_{t-1}(t-1) + S_t}{t} \tag{4}$$

Thus, m_t is the mean spill size over the previous t periods. When we do not have very long history, a large spill will result in a significant increase in the estimate of m. Throughout our analysis, we are going to concentrate on scenarios where t is not infinitely large. Even though the spill histories are quite large in reality, there is a time component to the mean of spills. Over time, tankers get larger and stronger, more and more remote places can be explored and exploited, traffic patterns and voyage characteristics change. We do not explicitly model the time component, but we account for it by assuming a relatively short history.

We define $\hat{V}_s$ as the value function in for period s without the downward rigidity constraint ($l_s \geq l_{s-1}$). Let $\hat{l}_s$ and $\widehat{\overline{S}}_{s+1}$ be the values that maximize this function. Starting from $s = T$ we have as $\hat{V}_T$:

$$\hat{V}_T = \max_{l_T} P(l_T) + C(l_T - m_T). \tag{5}$$

$\frac{\partial \hat{V}_T}{\partial l_T} = 0$ gives $\hat{l}_T$. The value function at time T, V_T, and the regulator's choice of level of regulation, l_T, can be characterized as

$$V_T = \begin{cases} P(\hat{l}_T) + C(\hat{l}_T - m_T) & \text{if } \hat{l}_T > l_{T-1} \\ P(l_{T-1}) + C(l_{T-1} - m_T) & \text{otherwise.} \end{cases} \tag{6}$$

$$l_T = \max\{\hat{l}_T, l_{T-1}\} \tag{7}$$

Also, remember that $\hat{l}_T = \hat{L}_T(m_T(S_T))$. Given V_T and $\hat{L}_T(m_T(S))$, we have

$$\hat{V}_{T-1} = \max_{\substack{l_{T-1} \\ \bar{S}_T}} \left(P(l_{T-1}) + C(l_{T-1} - m_{T-1}) + \int_0^{\bar{S}_T} V_T(l_{T-1}, m_T(S)) f(S; m_{T-1}) dS \right. \\ \left. + \int_{\bar{S}_T}^{\infty} V_T(\hat{L}_T(m_T(S)), m_T(S)) f(S; m_{T-1}) dS \right) \tag{8}$$

$\frac{\partial \hat{V}_{T-1}}{\partial \hat{l}_{T-1}} = 0$ yields $\hat{l}_{T-1}$ and $\frac{\partial \hat{V}_{T-1}}{\partial \hat{\bar{S}}_T} = 0$ yields $\hat{\bar{S}}_T$. For any period $t \leq s < T-1$, a similar relationship holds. Given V_{s+1} and $\hat{L}_{s+1}(m_{s+1}(S))$, we can characterize $\hat{V}_s$ as follows:

$$\hat{V}_s = \max_{\substack{l_s \\ \bar{S}_{s+1}}} \left(P(l_s) + C(l_s - m_s) + \int_0^{\bar{S}_{s+1}} V_{s+1}(l_s, m_{s+1}(S)) f(S; m_s) dS \right. \\ \left. + \int_{\bar{S}_{s+1}}^{\infty} V_{s+1}(\hat{L}_{s+1}(m_{s+1}(S)), m_{s+1}(S)) f(S; m_s) dS \right) \tag{9}$$

The Kuhn-Tucker conditions for $\hat{l}_s$ and $\hat{\bar{S}}_{s+1}$ are:

$$\frac{\partial \hat{V}_s}{\partial \hat{l}_s} = \left(P'(\hat{l}_s) + C'(\hat{l}_s - m_s) + \int_0^{\hat{\bar{S}}_{s+1}} \frac{\partial V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial \hat{l}_s} f(S; m_s) dS \right) \hat{l}_s = 0 \tag{10}$$

$$\frac{\partial \hat{V}_s}{\partial \hat{\overline{S}}_{s+1}} = (V_{s+1}(\hat{l}_s, m_{s+1}(\hat{\overline{S}}_{s+1})) - V_{s+1}(\hat{L}_{s+1}(m_{s+1}(\hat{\overline{S}}_{s+1})), m_{s+1}(\hat{\overline{S}}_{s+1})))f(\hat{\overline{S}}_{s+1}; m_s)\hat{\overline{S}}_{s+1}$$
$$= 0 \tag{11}$$

(10) yields $\hat{l}_s = \bar{\hat{l}}_s(\hat{\overline{S}}_{s+1}, m_s)$ and (11) gives $\hat{\overline{S}}_{s+1} = \overline{\overline{S}}_{s+1}(\hat{l}_s, m_s)$. We can simultaneously solve these two equations to get $\hat{l}_s = \hat{L}_s(m_s)$ and $\hat{\overline{S}}_{s+1} = \hat{\mathcal{S}}_{s+1}(m_s)$. When $l_{s-1} > \hat{l}_s$, $l_s = l_{s-1}$, the value function is denoted by $\tilde{V}_s$ and the threshold level of spill that maximizes $\tilde{V}_s$ is denoted by $\tilde{\overline{S}}_{s+1}$. $\tilde{V}_s$ is given by

$$\tilde{V}_s = \max_{\bar{S}_{s+1}} \Bigg(P(l_{s-1}) + C(l_{s-1} - m_s) + \int_0^{\bar{S}_{s+1}} V_{s+1}(l_{s-1}, m_{s+1}(S)) f(S; m_s) dS \\ + \int_{\bar{S}_{s+1}}^{\infty} V_{s+1}(\hat{L}_{s+1}(m_{s+1}(S)), m_{s+1}(S)) f(S; m_s) dS \Bigg) \tag{12}$$

The Kuhn-Tucker condition for $\tilde{\overline{S}}_{s+1}$ is:

$$\frac{\partial \tilde{V}_s}{\partial \tilde{\overline{S}}_{s+1}} = (V_{s+1}(l_{s-1}, m_{s+1}(\tilde{\overline{S}}_{s+1})) - V_{s+1}(\hat{L}_{s+1}(m_{s+1}(\tilde{\overline{S}}_{s+1})), m_{s+1}(\tilde{\overline{S}}_{s+1})))f(\tilde{\overline{S}}_{s+1}; m_s)\tilde{\overline{S}}_{s+1}$$
$$= 0 \tag{13}$$

which yields $\tilde{\overline{S}}_{s+1} = \overline{\overline{S}}_{s+1}(l_{s-1}, m_s)$. We can characterize the solution for V_s as

$$l_s = \max\{\hat{l}_s, l_{s-1}\} \tag{14}$$
$$\bar{S}_{s+1} = \{\overline{\overline{S}}_{s+1}(l_s, m_s)\}. \tag{15}$$

We are now ready to present our first result. We think of a regulator that came to power at time t, inheriting a regulation level l_{t-1}.

Result 1: The regulation level at time $\tau > t$, l_τ, is the maximum of $\{l_{t-1}, \hat{l}_t, \hat{l}_{t+1}...\hat{l}_\tau\}$.

Proof:

Recall that the $\hat{l}$'s are the solutions to the unconstrained problems. The regulator would choose this regulation level whenever it is feasible. Thus the solution to the regulator's problem at time τ can also be characterized in terms of the history of choices the regulator would have made, if regulations were not downward rigid.

Result 2: Regulatory reform falls short of the level desired by consumers, i.e. $\hat{l}_s < m_s$.

Proof:

If $\hat{l}_s > m_s$, we could increase political capital by lowering $\hat{l}_s$. Producers are happier at lower levels of regulation, so $P(l_s)$ would increase. $C(l_s - m_s)$ would also increase because the gap between the actual and the desired level of regulation would decrease. When $\hat{l}_s$ is decreased, so is $\widehat{\widehat{S}}_{s+1}$. Since the downward rigidity constraint is binding for l_{s+1} when $0 \leq S_{s+1} \leq \widehat{\widehat{S}}_{s+1}$, shrinking this range also provides an improvement.

If $l_s = m_s$, we could still increase political capital by lowering l_s. $P(l_s)$ would increase and the range where decisions are constrained will shrink, but $C(l_s - m_s)$ would deteriorate. There is an $l_s \leq m_s$ where the decline in $C(l_s - m_s)$ would equal the improvements in the rest of the terms.

Result 3: $\hat{l}(m)$ is an increasing function of m.

Proof:

We are going to prove this result by backward induction. The final period, T, does not include future value functions as the other time periods, so we are going to treat this period as special. We are first going to show that $\frac{d\hat{l}_T}{dm_T} > 0$[3] and $\frac{d\hat{l}_{T-1}}{dm_{T-1}} > 0$. Then we are going to assume that $\frac{d\hat{l}_{s+1}}{dm_{s+1}} > 0$ and show that, under this assumption, $\frac{d\hat{l}_s}{dm_s} > 0$. Since we have already shown that $\frac{d\hat{l}_{T-1}}{dm_{T-1}} > 0$, working backwards, we can show that $\frac{d\hat{l}_s}{dm_s} > 0$ for any $t \leq s < T-1$. The proof is less straightforward because along the way we also need to prove that $\frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1}\partial \hat{l}_s} > 0$ to get $\frac{d\hat{l}_s}{dm_s} > 0$ when $\frac{d\hat{l}_{s+1}}{dm_{s+1}} > 0$. We also prove this by backward induction: We first show it to be true for $T-1$. Then we assume it to be true for $s+1$ and show that it holds for s when it holds for $s+1$. Since we have shown it to hold for $T-1$, we can work backwards and demonstrate that it will hold for any $t \leq s < T-1$.

We start by showing that $\frac{d\hat{l}_T}{dm_T} > 0$. From (5), the first-order condition for $\hat{l}_T$ is:

$$P'(\hat{l}_T) + C'(\hat{l}_T - m_T) = 0 \tag{16}$$

If m_T were to change, $\hat{l}_T$ would adjust to keep the above equality unchanged. By differentiating both sides of the above equality by m_T, we get:

$$P''(\hat{l}_T)\frac{d\hat{l}_T}{dm_T} + C''(\hat{l}_T - m_T)\frac{d\hat{l}_T}{dm_T} - C''(\hat{l}_T - m_T) = 0 \tag{17}$$

[3]We are going to use $\frac{d\hat{l}_T}{dm_T}$ rather than $\frac{\partial \hat{l}_T}{\partial m_T}$ to denote comparative static derivatives.

which gives

$$\frac{d\hat{l}_T}{dm_T} = \frac{C''(\hat{l}_T - m_T)}{P''(\hat{l}_T) + C''(\hat{l}(m_T) - m_T)} \tag{18}$$

$C'' < 0$ and $P'' < 0$ so $\frac{d\hat{l}_T}{dm_T} > 0$.

Next we show that $\frac{d\hat{l}_{T-1}}{dm_{T-1}} > 0$. From (8), the first-order conditions for $\hat{l}_{T-1}$ and $\widehat{\widehat{S}}_T$ are:

$$\begin{aligned}\frac{\partial \hat{V}_{T-1}}{\partial \hat{l}_{T-1}} &= P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\widehat{\widehat{S}}_T} \frac{\partial V_T(\hat{l}_{T-1}, m_T(S))}{\partial \hat{l}_{T-1}} f(S; m_{T-1}) dS \\ &= 0 \end{aligned} \tag{19}$$

$$\frac{\partial \hat{V}_{T-1}}{\partial \widehat{\widehat{S}}_T} = (V_T(\hat{l}_{T-1}, m_T(\widehat{\widehat{S}}_T)) - V_T(\hat{L}_T(m_T(\widehat{\widehat{S}}_T)), m_T(\widehat{\widehat{S}}_T))) f(\widehat{\widehat{S}}_T; m_{T-1}) = 0. \tag{20}$$

Since $\hat{L}_T(m_T(\widehat{\widehat{S}}_T)$ is the unique maximum to $V_T(\hat{L}_T(m_T(\widehat{\widehat{S}}_T)), m_T(\widehat{\widehat{S}}_T))$, (20) implies:

$$\hat{L}_T(m_T(\widehat{\widehat{S}}_T)) - \hat{l}_{T-1} = 0. \tag{21}$$

Note that, from integration by parts,

$$\begin{aligned}\int_0^{\widehat{\widehat{S}}_T} \frac{\partial V_T(\hat{l}_{T-1}, m_T(S))}{\partial \hat{l}_{T-1}} f(S; m_{T-1}) dS = \left(\frac{\partial V_T(\hat{l}_{T-1}, m_T(S))}{\partial \hat{l}_{T-1}} F(S; m_{T-1}) \right)_0^{\widehat{\widehat{S}}_T} \\ - \int_0^{\widehat{\widehat{S}}_T} \frac{\partial^2 V_T(\hat{l}_{T-1}, m_T(S))}{\partial m_T \partial \hat{l}_{T-1}} \frac{\partial m_T(S)}{\partial S} F(S; m_{T-1}) dS.\end{aligned} \tag{22}$$

From (5),

$$V_T(\hat{l}_{T-1}, m_T(S)) = P(\hat{l}_{T-1}) + C(\hat{l}_{T-1} - m_T(S)) \tag{23}$$

and

$$\frac{\partial V_T(\hat{l}_{T-1}, m_T(S))}{\partial \hat{l}_{T-1}} = P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_T(S)). \tag{24}$$

Substituting (21) into this equation gives (16) and hence $\frac{\partial V_T(\hat{l}_{T-1}, m_T(\widehat{\widehat{S}}_T))}{\partial \hat{l}_{T-1}} = 0$. $F(0) = 0$ so the first term in (22) disappears. Differentiating (5) and using (4) gives

$$\frac{\partial^2 V_T(\hat{l}_{T-1}, m_T(S))}{\partial m_T \partial \hat{l}_{T-1}} \frac{\partial m_T(S)}{\partial S} \quad = \quad \frac{-C''(\hat{l}_{T-1} - m_T(S))}{T}. \tag{25}$$

so (19) reduces to

$$P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\widehat{\widehat{S}}_T} \frac{C''(\hat{l}_{T-1} - m_T(S))}{T} F(S; m_{T-1}) dS = 0 \tag{26}$$

We now differentiate (26) and (21) with respect to m_{T-1} and get

$$\begin{bmatrix} U & V \\ W & X \end{bmatrix} \begin{bmatrix} d\hat{l}_{T-1} \\ d\widehat{\widehat{S}}_T \end{bmatrix} = \begin{bmatrix} Y \\ Z \end{bmatrix} dm_{T-1} \tag{27}$$

where

$$
\begin{aligned}
U &= P''(\hat{l}_{T-1}) + C''(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\widehat{\overline{S}}_T} \frac{C'''(\hat{l}_{T-1} - m_T(S))}{T} F(S; m_{T-1}) dS && (28)\\
V &= \frac{C''(\hat{l}_{T-1} - m_T(\widehat{\overline{S}}_T))}{T} F(\widehat{\overline{S}}_T; m_{T-1}) && (29)\\
W &= -1 && (30)\\
X &= \frac{d\hat{l}_T}{dm_T}\frac{1}{T} && (31)\\
Y &= C''(\hat{l}_{T-1} - m_{T-1}) - \int_0^{\widehat{\overline{S}}_T} \frac{C''(\hat{l}_{T-1} - m_T(S))}{T} \frac{\partial F(S; m_{T-1})}{\partial m_{T-1}} dS && (32)\\
&\quad + \int_0^{\widehat{\overline{S}}_T} C'''(\hat{l}_{T-1} - m_T(S)) \frac{T-1}{T^2} F(S; m_{T-1}) dS \\
Z &= -\frac{d\hat{l}_T}{dm_T}\frac{T-1}{T}. && (33)
\end{aligned}
$$

$\frac{d\hat{l}_{T-1}}{dm_{T-1}}$ is given by

$$
\frac{d\hat{l}_{T-1}}{dm_{T-1}} = \frac{\begin{vmatrix} Y & V \\ Z & X \end{vmatrix}}{\begin{vmatrix} U & V \\ W & X \end{vmatrix}} \qquad (34)
$$

$U < 0$ by the second-order condition, $V < 0$ since $C'' < 0$, $W < 0$ and $X > 0$. This gives $\begin{vmatrix} U & V \\ W & X \end{vmatrix} < 0$. We can also determine the sign of $\begin{vmatrix} Y & V \\ Z & X \end{vmatrix}$. Integration-by-parts gives

$$
\int_0^{\widehat{\overline{S}}_T} \frac{C'''(\hat{l}_{T-1} - m_T(S))}{T} F(S; m_{T-1}) dS = -C''(\hat{l}_{T-1} - m_T(\widehat{\overline{S}}_T)) F(\widehat{\overline{S}}_T; m_{T-1}) \qquad (35)
$$

$$+\int_0^{\widehat{\widehat{S}}_T} C''(\hat{l}_{T-1}-m_T(S))\frac{\partial F(S;m_{T-1})}{\partial S}dS.$$

Substituting (36) and (29) into (33) gives:

$$\begin{aligned} Y &= C''(\hat{l}_{T-1}-m_{T-1}) - \int_0^{\widehat{\widehat{S}}_T} \frac{C''(\hat{l}_{T-1}-m_T(S))}{T}\frac{\partial F(S;m_{T-1})}{\partial m_{T-1}}dS \\ &\quad -(T-1)V + \frac{T-1}{T}\int_0^{\widehat{\widehat{S}}_T} C''(\hat{l}_{T-1}-m_T(S))\frac{\partial F(S;m_{T-1})}{\partial m_{T-1}}dS. \end{aligned} \tag{36}$$

Define

$$\begin{aligned} A &= C''(\hat{l}_{T-1}-m_{T-1}) - \int_0^{\widehat{\widehat{S}}_T} \frac{C''(\hat{l}_{T-1}-m_T(S))}{T}\frac{\partial F(S;m_{T-1})}{\partial m_{T-1}}dS \\ &\quad +\frac{T-1}{T}\int_0^{\widehat{\widehat{S}}_T} C''(\hat{l}_{T-1}-m_T(S))\frac{\partial F(S;m_{T-1})}{\partial m_{T-1}}dS. \end{aligned} \tag{37}$$

$A<0$ since $\frac{\partial F(S;m_s)}{\partial m_s}<0, \frac{\partial F(S;m_s)}{\partial S}>0$ and $C''<0$.

The determinant of $\begin{bmatrix} Y & V \\ Z & X \end{bmatrix}$ is $(YX-VZ)$. Substituting $Y=-(T-1)V+A$ and rearranging terms gives $YX-VZ=XA$ which is negative since we have shown $\frac{d\hat{l}_T}{dm_T}>0$. This gives $\begin{vmatrix} Y & V \\ Z & X \end{vmatrix}<0$. Since $\begin{vmatrix} U & V \\ W & X \end{vmatrix}$ is also negative, we get $\frac{d\hat{l}_{T-1}}{dm_{T-1}}>0$.

Now we are going to assume that $\frac{d\hat{l}_{s+1}}{dm_{s+1}}>0$. First-order conditions for $\hat{l}_s$ and $\widehat{\widehat{S}}_{s+1}$ are:

$$P'(\hat{l}_s)+C'(\hat{l}_s-m_s)-\int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1}\partial \hat{l}_s}\frac{1}{s+1}F(S;m_s)dS=0 \tag{38}$$

$$\hat{L}_{s+1}(m_{s+1}(\widehat{\widehat{S}}_{s+1})) - \hat{l}_s = 0 \tag{39}$$

Differentiating these two equations with respect to m_s we get:

$$\begin{aligned}
U &= P''(\hat{l}_s) + C''(\hat{l}_s - m_s) - \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^3 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial \hat{l}_s \partial m_{s+1} \partial \hat{l}_s} \frac{1}{s+1} F(S; m_s) dS &(40)\\
V &= -\frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(\widehat{\widehat{S}}_{s+1}))}{\partial m_{s+1} \partial \hat{l}_s} \frac{1}{s+1} F(\widehat{\widehat{S}}_{s+1}; m_s) &(41)\\
W &= -1 &(42)\\
X &= \frac{d\hat{l}_{s+1}}{dm_{s+1}} \frac{1}{s+1} &(43)\\
Y &= C''(\hat{l}_s - m_s) + \frac{s}{(s+1)^2} \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^3 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1}^2 \partial \hat{l}_s} F(S; m_s) dS &(44)\\
&\quad + \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1} \partial \hat{l}_s} \frac{1}{s+1} \frac{\partial F(S; m_s)}{\partial m_s} dS\\
Z &= -\frac{d\hat{l}_{s+1}}{dm_{s+1}} \frac{s}{s+1}. &(45)
\end{aligned}$$

Note that integration-by-parts gives:

$$\begin{aligned}
\int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^3 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1}^2 \partial \hat{l}_s} \frac{1}{s+1} F(S; m_s) dS &= \left(\frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1} \partial \hat{l}_s} F(S; m_s) \right)_0^{\widehat{\widehat{S}}_{s+1}} &(46)\\
&\quad - \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1} \partial \hat{l}_s} \frac{\partial F(S; m_s)}{\partial S} dS
\end{aligned}$$

So if $\frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1} \partial \hat{l}_s} > 0$ then we can show that $\frac{d\hat{l}_s}{dm_s} > 0$. $U < 0$ by the second-order condition, $V < 0$ if $\frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1} \partial \hat{l}_s} > 0$, $W < 0$ and $X > 0$ which gives $\begin{vmatrix} U & V \\ W & X \end{vmatrix} < 0$. Y

can again be rewritten as $Y = -(T-1)V + A$ where $A < 0$ which would give $\begin{vmatrix} Y & V \\ Z & X \end{vmatrix} < 0$.

We can also prove that $\frac{\partial^2 V_{s+1}(\hat{l}_s, m_{s+1}(S))}{\partial m_{s+1} \partial \hat{l}_s} > 0$ by backward induction. For $l > \hat{l}_T$, we have

$$\frac{\partial^2 V_T(l, m_T(S))}{\partial m_T \partial l} = -C''(l - m_T(S)) > 0. \tag{47}$$

For $l > \hat{l}_{T-1}$, we get

$$\begin{aligned} \frac{\partial^2 V_{T-1}(l, m_{T-1}(S)}{\partial m_{T-1} \partial l} &= -C''(l - m_{T-1}(S)) + C''(l - m_T(\widehat{\widehat{S}}_T)) \frac{T-1}{T} F(\widehat{\widehat{S}}_T; m_{T-1}) \\ & C''(l - m_T(\widehat{\widehat{S}}_T)) \frac{1}{T} F(\widehat{\widehat{S}}_T; m_{T-1}) \frac{\partial \widehat{\widehat{S}}_T}{\partial m_{T-1}} \\ & - \int_0^{\widehat{\widehat{S}}_T} C''(l - m_T(S)) \frac{T-1}{T} f(S; m_s) dS \\ & + \int_0^{\widehat{\widehat{S}}_T} C''(l - m_T(S)) \frac{1}{T} \frac{\partial F(S; m_s)}{\partial m_{T-1}} dS \end{aligned} \tag{48}$$

$\frac{\partial \widehat{\widehat{S}}_T}{\partial m_{T-1}} = -(T-1)$ since m_{T-1} only affects $\widehat{\widehat{S}}_T$ through m_T as $\frac{\partial l}{\partial m_{T-1}} = 0$ for $l > \hat{l}_{T-1}$. For $l > \hat{l}_s$:

$$\frac{\partial V_s(l, m_s(S))}{\partial l} = P'(l) + C'(l - m_s) - \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(l, m_{s+1}(S))}{\partial m_{s+1} \partial l} \frac{1}{s+1} F(S; m_s) dS \tag{49}$$

$$\begin{aligned} \frac{\partial^2 V_s(l, m_s)}{\partial m_s \partial l} &= -C''(l - m_s) - \frac{\partial^2 V_{s+1}(l, m_{s+1}(\widehat{\widehat{S}}_{s+1}))}{\partial m_{s+1} \partial l} \frac{s}{s+1} F(\widehat{\widehat{S}}_{s+1}; m_s) \\ & - \frac{\partial^2 V_{s+1}(l, m_{s+1}(\widehat{\widehat{S}}_{s+1}))}{\partial m_{s+1} \partial l} \frac{1}{s+1} F(\widehat{\widehat{S}}_{s+1}; m_s) \frac{\partial \widehat{\widehat{S}}_{s+1}}{\partial m_s} \end{aligned} \tag{50}$$

$$+\int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(l, m_{s+1}(S))}{\partial m_{s+1}\partial l} \frac{s}{s+1} \frac{\partial F(S; m_s)}{\partial S} dS$$
$$-\int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(l, m_{s+1}(S))}{\partial m_{s+1}\partial l} \frac{1}{s+1} \frac{\partial F(S; m_s)}{\partial m_s} dS$$

since $\frac{\partial l}{\partial m_s} = 0$. Also note that $\frac{\partial \widehat{\widehat{S}}_{s+1}}{\partial m_s} = -s$ so $\frac{\partial^2 V_s(l,m_s)}{\partial m_s \partial l}$ reduces to

$$\begin{aligned} \frac{\partial^2 V_s(l, m_s)}{\partial m_s \partial l} &= -C''(l - m_s) + \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(l, m_{s+1}(S))}{\partial m_{s+1}\partial l} \frac{s}{s+1} \frac{\partial F(S; m_s)}{\partial S} dS \\ &\quad - \int_0^{\widehat{\widehat{S}}_{s+1}} \frac{\partial^2 V_{s+1}(l, m_{s+1}(S))}{\partial m_{s+1}\partial l} \frac{1}{s+1} \frac{\partial F(S; m_s)}{\partial m_s} dS \end{aligned} \tag{51}$$

which is positive. Then $\frac{d\hat{l}_s}{dm_s} > 0$. Thus, we have shown that $\frac{d\hat{l}_{s+1}}{dm_{s+1}} > 0$ implies $\frac{d\hat{l}_s}{dm_s} > 0$. This, combined with the earlier result that $\frac{d\hat{l}_{T-1}}{dm_{T-1}} > 0$, establishes that $\frac{d\hat{l}_s}{dm_s} > 0$ for $T - 1 > s \geq t$. The implication of these results is that a very large spill will cause a significant increase in the level of regulation when we do not have a long history, unless regulations are at a high level to begin with. The regulator does not take into account the reliability of its estimate for the mean spill size. If a catastrophic spill were to occur when reliable information on the distribution of spills was not available, this would raise the regulations to a level that could prove to be very costly for future periods.

4 Analytic Solution for Two Periods

In this section, we analytically solve the model for two periods. We adopt the following functional forms for producers' satisfaction and consumers' satisfaction:

$$P(l) = 100 - 0.5 * l^2 \tag{52}$$

and

$$C(l - m) = 100 - 0.5 * (l - m)^2. \tag{53}$$

Let T be the terminal period. Then $\hat{l}_T$ is given by:

$$\frac{\partial \hat{V}_T}{\partial \hat{l}_T} = P'(\hat{l}_T) + C'(\hat{l}_T - m_T(S_T)) = 0 \tag{54}$$

The solution for T is:

$$\begin{aligned} l_T &= m_T(S_T)/2 \quad \text{if } m_T(S_T)/2 > l_{T-1} \\ & \quad l_{T-1} \qquad\qquad \text{otherwise.} \end{aligned} \tag{55}$$

For $T - 1$

$$\frac{\partial \hat{V}_{T-1}}{\partial \hat{l}_{T-1}} = P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\hat{\overline{S}}_T} \frac{\partial V_T(\hat{l}_{T-1}, m_T(S_T))}{\partial \hat{l}_{T-1}} f(S_T; m_{T-1}) dS_T = 0 \tag{56}$$

where $V_T = P(l_{T-1}) + C(l_{T-1} - m_T)$ since over the range from 0 to $\widehat{\widehat{S}}_T$ $\hat{l}_T < l_{T-1}$.

$$\frac{\partial \hat{V}_{T-1}}{\partial \hat{l}_{T-1}} = P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\widehat{\widehat{S}}_T} \left(P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m(S_T)) \right) f(S_T; m_{T-1}) dS_T$$

$\hat{l}_{T-1}$ is given by:

$$-4\hat{l}_{T-1} - e^{(T-1-2T\frac{\hat{l}_{T-1}}{m_{T-1}})} m_{T-1}/T = -2m_{T-1} \tag{57}$$

5 A Numerical Example

To see if this model gives reasonable solutions, we provide a numerical example for three periods. For the terminal period we have:

$$\frac{\partial \hat{V}_T}{\partial \hat{l}_T} = P'(\hat{l}_T) + C'(\hat{l}_T - m_T) = 0 \tag{58}$$

For $\tau < T$:

$$\begin{aligned} \frac{\partial \hat{V}_\tau}{\partial \hat{l}_\tau} &= P'(\hat{l}_\tau) + C'(\hat{l}_\tau - m_\tau) + \int_0^{\widehat{\widehat{S}}_\tau} \frac{\partial V_{\tau+1}(\hat{l}_\tau, m_{\tau+1}(S))}{\partial \hat{l}_\tau} f(S_{\tau+1}; m_\tau) dS_{\tau+1} = 0 \qquad (59) \\ \frac{\partial \hat{V}_\tau}{\partial \hat{l}_\tau} &= P'(\hat{l}_\tau) + C'(\hat{l}_\tau - m_\tau) + \int_0^{\widehat{\widehat{S}}_{\tau+1}} (P'(\hat{l}_\tau) + C'(\hat{l}_\tau - m_{\tau+1}(S_{\tau+1})) f(S_{\tau+1}; m_\tau) dS_{\tau+1} + \\ & \int_0^{\widehat{\widehat{S}}_{\tau+1}} \left(\int_0^{\widehat{\widehat{S}}_{\tau+2}} (P'(\hat{l}_\tau) + C'(\hat{l}_\tau - m_{\tau+2}(S_{\tau+2})) f(S_{\tau+2}; m_{\tau+1}) dS_{\tau+2} \right) f(S_{\tau+1}; m_\tau) dS_{\tau+1} + \ldots.. \\ & \int_0^{\widehat{\widehat{S}}_{\tau+1}} \ldots. \left(\int_0^{\widehat{\widehat{S}}_T} (P'(\hat{l}_\tau) + C'(\hat{l}_\tau - m_T(S_T))) f(S_T; m_{T-1}) dS_T \right) \ldots f(S_{\tau+1}; m_\tau) dS_{\tau+1} = 0 \end{aligned}$$

The explicit formulations for the 1st and 2nd periods are reported in the technical appendix. The solution algorithm is described in Table 1. m_{t-1} is our best guess at the beginning of time t conditional on spills observed so far. In the example we present, we assume the true distribution of spills to be $\frac{e^{-\frac{S}{100}}}{100}$.

In Table 2, we present the numerical solution for the three period problem for three scenarios. Spill sizes for all the scenarios are generated from an exponential distribution with mean spill size equal to 100. In the first scenario, there is a large spill in the third period. The effect of this spill on the regulation level is to almost double it. In this scenario, the estimate of mean spill size in the first and second periods are close to the true mean. In the second scenario, the estimate of mean spill size if gradually increased, accompanied by a gradual increase in the regulation level. In the third scenario, there is a large spill in the second period that also has a dramatic effect on the regulation level.

6 Extensions

It is possible to extend this model in a number of insightful ways. The introduction of enforcement of regulations could produce interesting results because this would weaken the downward rigidity constraint. This would certainly make the model more realistic because as far as oil spill regulation is concerned, it is well acknowledged that regulators may not enforce laws that are passed today but come into effect in the future, at all and may only partially enforce existing laws[4]. After a rash of serious spills worldwide in 1978, an executive

[4]See (Cohen 1987), (Epple & Visscher 1984)

Table 1: Solution Algorithm

1. Define
    - $P(l) = 100 - 0.5 * l^2$
    - $C(l - m) = 100 - 0.5 * (l - m)^2$
2. Initialize
    - $t = 1$
    - $T = 3$
    - $m_{t-1} = 100$
    - $\widehat{\widehat{S}}_{T+1} = 0$
3. Generate spills
    (a) $s = t$
    (b) Pick S_s from $f(S; 100) = \frac{e^{-\frac{S}{100}}}{100}$
    (c) $m_s = \frac{m_{s-1}(s-1)+S_s}{s}$
    (d) s=s+1
    (e) If $s \leq T$, go to (b)
    (f) Else continue
4. Solve $\frac{\partial \hat{V}_T}{\partial \hat{l}_T} = 0$ for $\hat{l}_T$
5. Solve for $\hat{l}$ and $\widehat{\widehat{S}}$ for the other periods
    (a) $s = T - 1$
    (b) Assume $l_s^{(0)} = \hat{l}_{s+1}$
    (c) Iterate over i
        i. Solve $\frac{\partial \hat{V}_s}{\partial \widehat{\widehat{S}}_{s+1}} = 0$ for $\widehat{\widehat{S}}_{s+1}^{(i)}$
        ii. Solve $\frac{\partial \hat{V}_s}{\partial \hat{l}_s} = 0$ for $\hat{l}_s^{(i)}$.
        iii. If $|\hat{l}_s^{(i)} - l_s^{(i)}| > \epsilon$
            A. $l_s^{(i+1)} = \frac{l_s^{(i)} + \hat{l}_s^{(i)}}{2}$
            B. Go to i.
        iv. Else
            A. $s = s - 1$
            B. If $s \geq t$, go to (b)
            C. Else continue
6. Solve for l
    (a) $s = t$
    (b) If $\hat{l}_s > l_{s-1}, l_s = \hat{l}_s$
    (c) Else $l_s = l_{s-1}$
    (d) s=s+1
    (e) If $s \leq T$, go to (b)
    (f) Else continue
7. End

Table 2: Examples

Period	Spill	Estimate of Mean Spill	Regulation Level
1	108.37	108.37	46.19
2	88.15	98.26	46.19
3	322.11	172.88	86.44
1	30.33	30.33	15.09
2	98.75	64.54	29.77
3	120.02	83.03	41.52
1	87.71	87.71	43.48
2	238.63	163.17	75.28
3	111.76	146.03	75.28

Spills generated from an exponential distribution with mean 100.

order, which never became law, mandated double hulls for all new additions to the US tanker fleet. The OPA also mandated double hulls for all new and existing tankers. The mandate is enforced for new tankers but it is not clear if the mandate will be strictly enforced for existing tankers when the time comes (2015) especially if the recent spill history by then does not involve a large spill. With enforcement in the model, we are likely to see harsher regulations in earlier periods if the regulator is allowed to choose how much to enforce and the consumers and producers respond to enforcement as well as the regulation level. When the estimate of mean spill size decreases, we are likely to see lax enforcement. Regulatory reform would likely be accompanied by full enforcement because the regulator would be making the optimal choice given available information at the time, so full enforcement of these regulations would be optimal. There is nothing in the model to suggest that the regulator would choose harsher than necessary regulations for the current period and then enforce them partially. A risk averse regulator may exhibit such behavior, however.

It would also be interesting to analyze a scenario where the regulator can affect the distribution of spills. The model in its present form would not produce results that are rich in policy implications since producers are negatively affected by the level of regulation and consumers are affected only by the gap between the actual level of regulation and their perception of what it should be. Stricter regulation would decrease the mean spill size but would make producers unhappy and would not affect consumers as long as the gap between the actual and their perceived optimal level of regulation is not large. However, if consumers care about the mean spill size, and dislike high average spills, then the regulator would choose to regulate at a level that reduces the mean spill size. If we allow the consumers to dislike high levels of regulation as well as large mean spills, the regulator could choose to regulate at a level that either reduces or increases the mean spill size depending on the consumers' degree of aversion to high levels of regulation.

Finally, we have used a very simple update rule for beliefs. The agents simply average over past realizations of spills to estimate the mean spill size. When a long history of spills is available this approach would work. When the history of spills is not very long as would be the case if the distribution of spills is changing over time, a Bayesian update rule would be more realistic and possibly would not produce as extreme reactions to medium-large spills as the model we have presented does. More importantly, very small spills lower the mean spill size when averaging is used. The probability of small spills is high given an exponential probability distribution as we have assumed. A Bayesian updating rule would not reduce the mean spill size as fast when small spills occur. On the other hand, the response to very large spills would be amplified when the extremely low probability of such outcomes is taken into account. However, the convergence to the correct estimate of mean spill size would be faster under a Bayesian update rule which in turn would lower the likelihood that the society would end up at a regulation level that is too high.

7 Conclusion

We have presented a model of endogenous oil spill regulation under uncertainty in which catastrophic spills like the Exxon Valdez would lead to major regulatory reforms. In the context of this model, we argue that when good estimates for the distribution of spills are not available, and a low probability large spill occurs, regulations may reach a level that is too high. The regulations are too high in the sense that they are too costly for society given the true distribution of spills. Under the assumption of downward rigidity, there is a strong case to be made for the need for good estimates of the distribution of spills.

A Technical Appendix

$$
\begin{aligned}
\frac{\partial \hat{V}_{T-1}}{\partial \hat{l}_{T-1}} &= P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\hat{\hat{S}}_T} \frac{\partial V_T(\hat{l}_{T-1}, m_T(S_T))}{\partial \hat{l}_{T-1}} f(S_T; m_{T-1}) dS_T \\
\frac{\partial \hat{V}_{T-1}}{\partial \hat{l}_{T-1}} &= P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_{T-1}) + \int_0^{\hat{\hat{S}}_T} \Big(P'(\hat{l}_{T-1}) + C'(\hat{l}_{T-1} - m_T(S_T)) \Big) f(S_T; m_{T-1}) dS_T \\
\frac{\partial \hat{V}_{T-2}}{\partial \hat{l}_{T-2}} &= P'(\hat{l}_{T-2}) + C'(\hat{l}_{T-2} - m_{T-2}) + \int_0^{\hat{\hat{S}}_{T-1}} \frac{\partial V_{T-1}(\hat{l}_{T-2}, m_{T-1}(S_{T-1}))}{\partial \hat{l}_{T-2}} f(S_{T-1}; m_{T-2}) dS_{T-1} \\
\frac{\partial \hat{V}_{T-2}}{\partial \hat{l}_{T-2}} &= P'(\hat{l}_{T-2}) + C'(\hat{l}_{T-2} - m_{T-2}) + \int_0^{\hat{\hat{S}}_{T-1}} \Big(P'(\hat{l}_{T-2}) + C'(\hat{l}_{T-2} - m_{T-1}(S_{T-1})) \\
&\quad + \int_0^{\hat{\hat{S}}_T} \left(\frac{\partial V_T(\hat{l}_{T-2}, m_T(S_T))}{\partial \hat{l}_{T-2}} \right) f(S_T) \Big) f(S_{T-1}; m_{T-2}) dS_{T-1} \\
\frac{\partial \hat{V}_{T-2}}{\partial \hat{l}_{T-2}} &= P'(\hat{l}_{T-2}) + C'(\hat{l}_{T-2} - m_{T-2}) + \int_0^{\hat{\hat{S}}_{T-1}} \Big(P'(\hat{l}_{T-2}) + C'(\hat{l}_{T-2} - m_{T-1}(S_{T-1}))
\end{aligned}
$$

$$+\int_0^{\hat{\hat{S}}_T} \left(P'(\hat{l}_{T-2}) + C'(\hat{l}_{T-2} - m_T(S_T))\right) f(S_T)dS_T\Big) f(S_{T-1}; m_{T-2})dS_{T-1}$$

B Appendix: Oil Spill Regulation

This appendix reviews the evolution of US oil spill regulation. It is intended to give the reader an understanding of how the federal and state governments have chosen to regulate tanker operators over the years. The emphasis is on developments since the 1969 Santa Barbara oil spill since prior regulations were aimed mainly at reducing intentional rather than accidental oil pollution.

B.1 Federal Regulation of Oil Spills

Although the first set of regulations pertaining to discharge of substances into US waters dates back to the 1899 Rivers and Harbors Act, the Oil Pollution Control Act (OPCA) of 1924 was the first comprehensive attempt at reducing oil pollution. The Federal Water Pollution Act (FWPA) in 1948 contained the OPCA and constituted a more comprehensive approach to water quality issues. As a reaction to well-publicized oils spills in the 60's, especially the 1969 Santa Barbara oil spill, FWPA was amended in 1970 and a provision dealing with spills of oil and hazardous substances, which is presently the section 311 of the Clean Water Act, was added. A federal fund to finance the cleanup of spills was established. The fund had the right to assess its costs against the responsible parties.

The 1972 Amendments represented a complete rewriting of the Act. This is what has become to be known as the Clean Water Act (CWA). The 1978 amendments affected the provisions relating to spills of hazardous substances.

The Clean Water Act contains a system for regulating spills. This system is composed of two components: regulations governing spill control and prevention equipment, and a system of penalties and liabilities, supplemented by a requirement for notification in the event a spill occurs.

Spill Prevention and Control

The EPA has a regulation that requires facilities that might spill or leak oil to prepare "spill prevention control and countermeasure" (SPCC) plans. Failure to prepare and maintain a SPCC plan subjects violators to penalties of up to $5,000 per day. The high cost of implementing these plans has resulted in spotty compliance. In the event that a spill occurs in amounts exceeding the "harmful" quantity as designated by EPA under section 311, the facility would then be required to submit a report to EPA and consider what measures are needed to prevent recurrence. EPA may then require an appropriate amendment to the plan.

Penalties, Notification and Cleanup Liability

In EPA's regulations, a "harmful" quantity of oil is any amount that creates a "film or sheen" on the water. Any discharge in excess of the designated quantity is subject to two civil penalties under section 311. One penalty is assessed by the Coast Guard and may not exceed $5,000. The other penalty is assessed by the EPA and may not exceed $50,000, except that it may go up to $250,000 if there is negligence on behalf of the owner, operator or person in charge. The Coast Guard penalty is assessed in an administrative proceeding, while EPA must proceed in a federal district court.

Any discharge over the EPA-designated quantity must also be reported immediately to EPA or the Coast Guard; a failure to do so entails an additional criminal penalty of up to $10,000 and one year's imprisonment.

The most serious financial exposure in the case of a sizable spill of oil or a hazardous substance can arise from the cleanup expense. Section 311(c) authorizes EPA and the Coast Guard to "remove" any spill of oil that is "harmful", and the company is liable to reimburse the Government for its removal costs up to $50,000, with no limit if negligence is involved. (Different liability limits apply to vessels. Vessel owners and operators must provide evidence that they can meet cleanup costs in the amount of $100 per registered ton of the vessel up to a maximum of $14 million.) The costs of oil spill cleanup damages may also be covered by the Offshore Oil Pollution Compensation Fund established under the Outer Continental Shelf Lands Act by the 1978 Amendments, to be funded by fees collected on oil obtained from the Outer Continental Shelf (OCS) which is defined as the area that lies beyond three miles from the coastline of the states to a distance of about 200 miles.

The inadequacy of the liability provisions became apparent soon after passage of the Act. But controversy over issues like what oil spill liability limits should be and whether Congress should preempt state laws plagued efforts to further amend the CWA. As a reaction to a rash of oil spills in the late 1980's, especially the Exxon Valdez catastrophe (others include the World Prodigy running aground on Breton Reef near Rhode island on June 23, 1989, releasing 294,000 gallons of home heating oil into Narasangett Bay, and the American Trader spilling approximately 400,000 gallons of oil off the Southern California coast on Feb. 7, 1990) Congress realized that the federal scheme for controlling spills was inadequate. In the Valdez spill 240,000 barrels of oil were spilled, eventually covering 3000 square miles of the Pristine William Sound area in Alaska with cleanup costs surpassing $2 billion. The maximum liability levels in the CWA were much too low for this size of a spill, and the Act had no control with respect to personnel or tanker standards. The fund authorized for cleanup costs contained only $7 million. The Oil Pollution Act (OPA) was enacted in 1990 to correct the inadequacies of existing regulations.

Oil Pollution Act of 1990

The Oil Pollution Act of 1990 has three important aspects. Liability for responsible parties is increased, federal cleanup facilities are enhanced and standards in selecting personnel and construction of new tankers are imposed. Liability provisions cover oil spills in the 200 mile coastal zone and shorelines. Liability limits are increased from the $150/ton under the CWA to $1200/ton. In the event of negligence, misconduct or violation of regulations liability is unlimited. The OPA (the House reversed its position here.) does not preempt state law, so responsible parties may be liable for greater amounts under state laws.

An Oil Spill Liability Trust Fund of $1 billion was created. This fund is designed to pay for cleanups in situations such as insolvency of the responsible party or harm in excess of that party's liability limitation.

The OPA significantly tightens standards for personnel staffing, training and licensing, with special emphasis on preventing alcohol and drug related problems. Construction standards now require that all new tankers have double hulls and by 2015 all existing single-hulled vessels will be phased out.

B.2 State Regulation of Oil Spills

Initially states that were concerned about oil pollution of their waters imposed criminal penalties on offenders. Massachusetts Statute which originated in 1929 imposed a fine on anyone who discharges oil into its waters. California Harbors and Navigation Code enacted in 1937 declared that it a crime to discharge oil. In the late 60s and early 70s, many states strengthened such measures or enacted new measures. Most states turned to civil liability as a means of preventing oil pollution. Some imposed strict liability (Oregon, California), others imposed liability for negligent behavior only (Georgia, Massachusetts). Other states focused on cleanup costs and made responsible parties liable for these. (New Hampshire) However, recognizing the difficulties of assessing damages, most states enacted complementary provisions imposing civil penalties.

If a spill occurs, the immediate concern is to clean it up. So many states, particularly coastal ones, established comprehensive oil spill containment laws. As of 1983, at least 19 states had enacted laws of this kind. Almost all state statutes require that the spill be promptly reported to a state agency. Some state legislation mandates that state agencies cleanup spills (Washington, Alaska) but at a minimum state law will fully authorize state agencies to undertake cleanup efforts if they so choose.

Recognizing that spills will occur, they adopt "state contingency plans" for a coordinated response to spills. Some states also require operators of oil production or transportation facilities to submit oil spill contingency plans to the state for review and approval.

Oil spill funds are available. These funds are generally quite small but financed by a tax on oil. Florida Coastal Protection Trust Fund at one point contained $55 million although the fund had a cap of $35 million, after which the tax that supported it was suspended.

By the end of 1990, a number of states had passed comprehensive legislation intended to improve their ability to prevent and respond to oil spills. First, states committed to increased planning efforts to enhance the responsiveness of both state agencies and the industry to the possibility of a large spill. Second, states increased the amount of money that would be accumulated in oil spill response funds. Third, they increased the penalty structure and liabilities for oil spills, as well as strengthening enforcement tools. Finally, many of the new state laws created commissions or other similar bodies to oversee the entire process.

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