MONITORING POLLUTION ACCIDENTS

by

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CONTENTS

ABSTRACT

We model the occurrence of an environmental accident as a stochastic event, in particular the situation of an oil spill is explored. Characteristics of the ship operator, and the different types of the ship's operating environment determine a stochastic process governing the time patterns and size of spills. It is shown that both the time distribution of different types of oil spills, and the distribution of spill size are affected by pollution control instruments such as fines, by enforcement effort, and by the alert level of the operating personnel.

Key Words: Optimization, Principal Agency, Environmental Pollution, Policy Measures.

1 INTRODUCTION

The primary aim of this paper is to present an economic framework broad enough to allow monitoring industrial pollution accidents (such as oil spill phenomena or chemical spills) without imposing differences in the approach between types of spills "a priori". We want a model in which all types of spills are probabilistically subject to reduction through changes in legislation and enforcement, that is we focus on preventive measures rather than spill response (Anderson et al., 1993). The underlying economic process is the maximization of expected profits by the facility (e.g. vessel owner). We assume that none of the choice variables in the profit maximization problem have deterministic relationships either with the amount of oil spilled or with the frequency with which oil spills occur. The oil spill phenomena is fundamentally stochastic in nature. More specifically, oil spills depend on a large number of factors, the year in which the ship was built, skills of the crew, level of maintenance of the equipment, weather conditions, many of which are under the control of the ship owner, but no one of them has deterministic relationship with the quantity spilled. These factors give rise to a systematic pattern in the series of oil spills, and what policy should do is to find out which policy instruments are susceptible of modifying the distribution of this series of events in the desired way.

Over the past few years there has been a series of models to explain the economic costs of marine pollution, e.g. Cohen (1986, 1987), Epple and Visscher (1984), Smets (1982) and Burrows et al. (1974).

Compared to these attempts the present model has two main features to explain oil spilling phenomena, first, it is based on viewing pollution accidents as Poisson type processes, and second, it considers such modelling form as the basis of exploring regulatory intervention via principal-agent relationships (Gottinger, 1996). For the first part, the stochastic model allows us an unfolding increasingly detailed view of how each step of the spilling process is affected by each policy measure and to compare the relative efficiencies of different measures in reducing spills.

For the second part, the situation modelled is for the principal (the regulatory agency) to write a `regulatory' contract for each agent (ship owner) specifying an output schedule and the agents choosing their activity levels (and levels of care). In such context, `truth-telling' must be a dominant strategy among all agents or must be enforced by the principal (Ching-to-Ma and J. Moore, 1986). We further assume that the principal observes the outcomes and is risk neutral, minimizing expected social damage. This is in line with considerations on general deterrence and accident cost reduction (Calabresi, 1970, Chapters 7-9; Burrows, 1980, Chapter 4).

2 A STOCHASTIC PROCESS MODEL

We first model the oil spill phenomenon as a Poisson process independent of whether regulatory monitoring and intervention takes place.

2.1 Ship Arrival Process

There are several types of ships arriving in a harbour. We assume that the types of ship arrive according to a Poisson process with different rates. Thus, the interarrival times for vessels of type *i* are an independent negative exponential random variable with parameter $._{i}$, having density:

$$f_i(t) = \zeta_i e^{-\zeta_i t} \qquad t \geq 0, \tag{2.1}$$

where $._{i}$ is the arrival rate of a ship type *i*, that is, the expected number of ships type *i* that arrive in a harbour per unit of time. In order to simplify matters, we identify with types of vessels mainly dominant carriers such as barges and tankers, i=1,2, but more generally, types could be classified as different potential maritime.

The combination of independence and exponentially distributed arrival times implies that the system has no memory, the arrival of one ship will not depend on the time elapsed since the arrival of the last ship. A Poisson process is being justified by observations that transportation patterns (at sea) generate accidents randomly in a Poisson distribution type manner.

Modelling the length of stay of a ship in a harbour implies also modelling its service time (the time spent unloading the cargo). We assume that service times are also independently and negative exponentially distributed, with parameter $*_{i}$. If a considerable amount of service time has elapsed for a ship, the implication will be that this ship will require more service which will result in more transfer operations. Thus, the density of the time till completion of service is given by:

$$f_i(t) = \delta_i e^{-\delta_i t} \qquad t \geq 0. \tag{2.2}$$

where $*_{i}$ is the serving rate for a ship type *i*, that is, the expected number of ships type *i* that are served in a harbour per unit of time.

The number of ships in the harbour changes with time. For every $t \geq 0$ let $N_i(t)$ be the random variable that indicates the number of ships of type *i* in the harbour. We are interested in the steady state behaviour of the system, the best description of the long run behaviour. Assuming that ships are served immediately on arrival, the steady state density is a Poisson density with parameter D_i. See Karlin and Taylor (1975). That is,

$$\lim_{t\to\infty} P|N_i(t)=n_i| \;=\; \Phi_i(n_i) \tag{2.3}$$

where:

$$\Phi_i(n_i)=\frac{\rho_i^{n_i}\;e^{-\rho_i}}{n_i!} \qquad n_i\geq 0. \tag{2.4}$$

Note that $\rho_i=\dfrac{\zeta_i}{\delta_i}$ for all ships type *i*.

An immediate consequence of this is that the steady state average number of ships in the harbour is,

$$\lim_{t\to\infty} E(N_i(t)) \;=\; \sum\nolimits_{n_i\geq 0}^{\infty} n_i\Phi(n_i) \;=\; \rho_i. \tag{2.5}$$

For $t \geq 0$ let $N(t) = \sum\nolimits_{i=0}^{\infty} N_i(t)$ be the random variable giving the total number of ships in the harbour at time *t*. Given that the stochastic processes $|N_i(t):t\geq 0|$ for all $i = 1,2,...m$ are independent, the steady state probability of total number of ships in the harbour is also a Poisson probability with parameter $\rho=\sum\nolimits_{i=1}^{m}\rho_i$. . That is $\lim_{t\to\infty} P|N(t)=n|$ is Φ (n) defined by:

$$\Phi(n)=\frac{\rho^n e^{-\rho}}{n!} \qquad n\geq 0. \tag{2.6}$$

2.2 Spill Arrival Process

Whether or not a spill occurs depends on physical characteristics of the vessel, the size and training of the crew and the shore personnel, as well as on the enforcement in the harbour. We reduce this complicated process into two competing effects: the probability that a spill occurs during any given instant that the ship is in harbour; and the time the ship spends in harbour. More specifically, the ship will stay in harbour for the random amount of time J_s (this service time is distributed as a negative exponential with parameter $*_i$ as above), and during each instant of time, *dt,* spent in harbour there is a probability $8_i dt$ of a spill occurring. We assume that 8_i depends on a vector of parameters $)_i$ including the level of enforcement, the training of the crew, year in which the ship was built, etc. But for now on we leave this dependence implicit. Letting $|S_i(t):t\geq 0|$ be a Poisson process with parameter 8_i, the random number of spills that occur by time *t* after the arrival of a ship is $S_i(t)$ if $t \leq J_s$ and $S_i(J_s)$ if
$t \geq J_s$. (Equivalently, $S_i(t 7 J_s)$ where $a 7 b = \min(a,b)$).

The assumption that the spill arrival process is Poisson implies that given the (j-1)'*th* spill, the waiting time till the *j'th* spill follows a negative exponential with parameter 8_i. That is,

$$f(\tau_a) = \lambda_i e^{-\lambda_i \tau_a} \tag{2.7}$$

When combined with the assumption of an independent negative exponential service time, the assumption that the spill arrival process is Poisson has the following implication: given that t has elapsed since the ship entered harbour, and independent of what has happened since the ship entered the harbour, the waiting time until either the next spill or the ship's departure is distributed as the minimum of two negative exponential random variables with parameter 8_i and $*_i$, e.g, a negative exponential with parameter $*_i$+8_i.

3 OPTIMIZATION PROBLEM OF A POLLUTION CONTROL AGENCY FOR PREVENTION

Up to this point we have assumed a stochastic process (Poisson Process) generating oil spills where both the actions that might be taken by ship owners to reduce the frequency and size of oil spills and the policies of the pollution control agency that might affect these actions are ignored. Suppose the goal of the agency is to minimize the social damage caused by oil spills during a period of time $(0,\tau]$. The social damage function is, of course, related to the damage function that assigns a cost level to each spill. For simplicity we take the social damage from all spills to be also the sum of the cost associated with each individual spill. Define $D(V(\tau))$ as the expected social damage caused by the volume of oil spilled during a period $(0,\tau]$ and $d(x_{ik})$ as the social cost of a spill x_{ik} (i.e. the *k-th* spill from a ship type *i*). Thus assuming that z_i spills have taken place during period $(0,\tau]$ from ships type *i*, then $D(V(\tau)) = E(\ldots) \sum_{i=1}^{M} \sum_{k=1}^{z_i} d(X_{ik})$. If $d(x_{ik}) = ax_{ik}$ for some constant a then the damage caused at the end of a period of time would not depend on the size of each of the spills but only on the final amount of oil spilled during the period $(0,\tau]$. If $d(x_{ik})$ is not linear the temporal damage function can depend not only on the number of oil spilled but also on the number of spills and their respective size. At the moment we assume that $d(x_{ik})$ is a linear function of the volume of oil spilled. Thus minimizing the expected volume of oil spilled is equivalent to minimizing the social damage $D(V(\tau))$.

The agency can use several types of policy measure. At present two main types of pollution control policies are used: technological standards and economic incentives. With the use of technological standards, the government normally tells firms what type of equipment they must install and how the equipment must be operated. It could involve an annual check for compliance with pollution prevention and navigation safety. Economic incentives are incorporated into the expected penalty function facing ship owners for pollution. The expected penalty conditioned on a spill being made is the product of the fine levied for pollution and the probability of a polluter being detected. Naval police monitoring uses two methods for detecting oil spills: first, they randomly monitor transfer operations and, second they patrol harbours and other areas looking for oil spills (Tebeau and Lissauer, 1993). The probabilities of detection and the response of ship owners to these measures depend on the hours devoted to them. In this paper we also consider how the economic incentives affect the probability of spilling and the spill size. These measures (i.e. monitoring transfer operations and harbour patrols) have a long run and short run effect on the ship behaviour. The agency reallocates effort periodically around some long average. Ship owners do not know "ex ante" the pollution control enforcement effort level for the period of their arrival in the harbour, but they are assumed to know the long run average level of total enforcement effort. They react to the overall long run expected enforcement level.

Once a ship arrives in harbour, the ship operator learns the number of ships in harbour and the enforcement effort level during this period. We expect ship owners to increase the level of care if the frequency of harbour patrols and the probability of monitoring during their stay in the harbour are larger than the average. Also we expect that if the ship is chosen to be monitored the ship owner will further increase the measures against pollution. Those are the short run or immediate effects of the pollution control policies. The optimization problem is described in terms of the volume of oil spilled and spill size. The pollution control policy instruments give incentives to decrease the expected volume of oil spilled. We assume that ship owners act so as to decrease the expected volume of oil spilled with increase in the level of enforcement effort. However, the volume spilled is equal to the number of spills times the average spill size. The optimization problem is solved only for two types of ships: tankers and barges. There is no modelling loss of generality, the conclusions can be generalized to the case of m types of ships. This model does not imply that the agency randomly chooses the ships to be monitored. The agency policy takes into account the differences between types of ships, the model permits classification of ships in different categories depending on their history of pollution prevention and safety violations.

In what follows we look at the long run effects of the enforcement effort stating the problem. Then we focus on the effect of policy instruments in the short run, on an individual ship and at the harbour level. We solve the short run agency problem of choosing the optimal number of ships monitored and the optimal frequency of harbour patrols.

3.1 Long Run Effects of Enforcement Effort

We assume that ship owners in deciding the long run level of investment in pollution control and prevention equipment only take into consideration the long run expected cost in the harbours of interest. Some pollution prevention equipment represents a large investment for ship owners. To build a tanker with double hull, slop or segregated ballast tanks or to install discharge containers is too costly to respond only to short run changes in pollution prevention measures. Pollution control measures include, in addition to monitoring of transfer operations and harbour patrols, the level of fines, frequency of examinations, clean up costs and level of equipment standards required by legislation. Also, since ships operate in different harbours, ship owners do not know the specific harbour they will visit when they make the long run investment decisions. Therefore, they will have to consider the average enforcement level across harbours. The agency optimizes the allocation of effort each period of time but ship owners are assumed to only take into account the steady state (i.e. long run) expected enforcement effort level for investment in pollution prevention equipment.

If there are any costs to be saved by reducing the frequency and size of oil spills profit maximizing ship owners will reduce them. We assume that in the long run, given the cost in pollution prevention equipment, ship owners take into account the overall level of enforcement effort, but in the short run when they actually arrive in a harbour they also react to that day's enforcement effort. Short run policy measures are important because most oil spills done during routine operations are caused by improper operations of equipment and human error. These accidents can be eliminated or reduced with policy measures that give incentives to perform appropriately each operation in the moment that the operation is taking place. The only way to lower expected pollution cost is having the ships perform the operations carefully. We expect the probability and size of spills to decrease with increases in the probability of monitoring and frequency of transfer operations. Next we discuss in detail these short run effects.

3.2 Short Run Effects Of Enforcement Effort

We begin by considering the short run responses of individual ships to pollution prevention measures. There are three types of short-run responses: (i) the response of a specific ship whose oil transfer operations are monitored, (ii) the responses of all ships of a specific type to the probability of monitoring that type of ship, and (iii) the responses of all ships of all types to the amount of harbour patrols.

The goal of the agency in the short run is to minimize the volume of oil spilled during a period of time $(0,\tau]$. During this period the agency decides how to allocate optimally the enforcement effort hours available among the different type of policy measures. We assume the regulatory agency chooses the number of each type of ship to be monitored and the harbour patrol frequency to minimize the volume of oil spilled.

In each period of time $(0,\tau]$ the agency faces a constraint. It has to allocate the total man-hours available $e(t)$, to monitoring transfer operations and to harbour patrols. An optimal allocation of enforcement effort by the agency, in general, will depend on the response of the ship owners to the policy measures. The ship owner's short run behaviour is not explicitly modelled in this paper. Assuming that the owners choose the pollution prevention measures that maximize their profit, the frequency and spill size distributions will be influenced by these short run ship owners profit maximization decisions. We expect the volume of oil spilled to decrease when either the probability of inspection or the frequency of harbour patrols increase.

When a ship enters in a harbour, there is a level of investment in pollution control equipment that has been chosen by ship owners depending on the long run steady state level of enforcement effort. The long run characteristics of the spill size distribution function cannot be changed, but there are actions that ship owners can take in the short run to lower the expected pollution. For example, increasing the number of crew members in performing transfer operations, increasing the maintenance level of the pollution prevention equipment, and following more closely safety procedures. These measures will reduce the probability of a spill occurring and the spill size.

Monitoring transfer operations has two types of effects in the short run: a public and a private good effect. The probability of being monitored affects all ships. Since ships "ex-ante" do not know if they will be monitored, they can be expected to increase the pollution prevention measures and level of care with increases in the probability of being monitored - this is the public deterrence effect. A proportion of ships are actually monitored, and the reduction on the expected volume of oil spilled on these ships is the private good effect. Define $''_I$ as the proportion by which a tanker's expected volume of oil spilled is reduced if the tankers is monitored. That is, $''_I$ represents the private good effect of monitoring a transfer operation.

The volume of oil spilled by a tanker depends on the probability of monitoring a tanker P_I, and on the man-hours devoted to harbour patrols f_H during the period of time $(0,\tau]$ that the tanker is in the harbour. $P_T = \frac{m_T}{n_T}$ where m_I is the number of tanker monitored in the harbour and n_I is the number of tankers that will transfer oil in the harbour during the period $(0,\tau]$. We assume that when the agency chooses the enforcement effort level for that period of time the number of ships of each type that visit the harbour is known. Similarly, the volume of oil spilled by barges depends on the probability of monitoring a barge, P_B, and on the man-hours devoted to harbour patrols f_H.

Define $V^T(P_T, f_H \mid \mathscr{E})$ and $V^B(P_B, f_H \mid \mathscr{E})$ as the random volume of oil spilled by a tanker and barge, respectively, before being monitored, where $\mathscr{E}$ is the long run enforcement effort level. Let S_I be the random number of spills that occur during a transfer operation from a ship type I. Thus, the volume of oil spilled by a tanker during its stay in the harbour $(0,\tau]$ if it has not been monitored is:

$$V^{\mathrm{T}}\ (P_{\mathrm{T}},f_H\ |\ \mathscr{E}\ )\ =\ \sum_{Z_i=0}^{S_{\mathrm{T}}}\ X_{Z_i}^{T}\ (P_{\mathrm{T}},f_H\ |\ \mathscr{E}\ ). \tag{3.1}$$

and for a barge,

$$V^{B}\ (P_B,f_H\ |\ \mathscr{E}\ )\ =\ \sum_{Z_i=0}^{S_B}\ X_{Z_i}^{B}\ (P_B,f_H\ |\ \mathscr{E}\ ). \tag{3.2}$$

The volume of oil spilled by ships that have been actually monitored is $"_I\ V^I$ and $"_B\ V^B$ where $0 \le\ "_I \le\ "_B \le 1$.

Define $EV^{\mathrm{T}}\ (P_{\mathrm{T}},f_H\ |\ \mathscr{E}\ )$ and $EV^{B}\ (P_B,f_H\ |\ \mathscr{E}\ )$ to be the expected volume of oil spilled by tankers and barges, respectively, before being monitored. By recalling that $S_I(t)$ is the random variable that represents the number of oil spills that a ship type I made by time t after its arrival in the harbour, the expected volume of oil spilled by tanker is,

$$EV^{\mathrm{T}}(P_{\mathrm{T}},f_H\ |\ \mathscr{E}\ )\ =\ E\left(\sum_{Z_i=0}^{S_{\mathrm{T}}}\ X_{Z_i}^{\mathrm{T}}(P_{\mathrm{T}},f_H\ |\ \mathscr{E}\ )\right) \tag{3.3}$$

$$= E(S_I)E(X^I).$$

$$= 8_I E(X^I).$$

and for the case of barges,

$$EV^{B}(P_B,f_H\ |\ E)\ =\ E\left(\sum_{Z_i=0}^{S_B}\ X_{Z_i}^{B}(P_B,f_H\ |\ \mathscr{E}\ )\right) \tag{3.4}$$

$$= E(S_B(t))E(X^B).$$

$$= 8_{\mathrm{B}} E(X^B).$$

(with 8 appropriately defined as the spill parameter in the Poisson Process).

Given that there are n_I tankers in the harbour of which m_I have been monitored, the expected volume of oil spilled by tankers in the harbour is:

$$(n_{\mathrm{T}} - m_{\mathrm{T}})EV^{\mathrm{T}}(P_{\mathrm{T}},f_H) + m_{\mathrm{T}}\,\alpha_{\mathrm{T}}\,EV^{\mathrm{T}}(P_{\mathrm{T}},f_H).$$

Monitoring a transfer operation includes checking that the pollution prevention and safety requirements are satisfied and witnessing that all steps of the transfer operation are done properly. For ship owners it should be cheaper to assure that equipment and crew perform properly during a transfer operation than being caught violating the law and forced to pay a penalty in the case of being monitored. A higher probability of being monitored raises the expected cost and thus induces greater "ex-ante" efforts by ship owners to decrease the chances of an oil spill. Therefore, we assume that the expected volume of oil spilled by a ship decreases with increases in the probability of monitoring. We also expect ship owners to correct first the defects that are cheapest, so that, the expected volume of oil spilled decreases at a rate in absolute value as monitoring increases. Thus,

$$V_{\mathrm{T}}^{\mathrm{T}} = \frac{\partial EV^{\mathrm{T}}(P_{\mathrm{T}},f_H)}{\partial P_{\mathrm{T}}}<0. \tag{3.5}$$

and

$$V_{\mathrm{TT}}^{\mathrm{T}} = \frac{\partial^2 \, EV^{\mathrm{T}}(P_{\mathrm{T}},f_H)}{\partial P_{\mathrm{T}}^2}>0. \tag{3.6}$$

Since increasing monitoring affects all ships of a given type "ex-ante", we refer to this as the public good effect of the probability of monitoring.

Monitoring transfer operations also has a private good effect. We also assume that the expected volume of oil spilled by a ship that is actually monitored is smaller than the expected volume of oil spilled if the ship is not monitored. We denote by $''_I$ the proportion by which a tanker's expected volume ("ex-ante") of oil spilled is reduced if the tanker is monitored. Therefore, $''_I$ represents the private good effect of actually monitoring a transfer operation. We assume that $''_I$ is the same for all tankers. From the assumptions made above, the expected volume of oil spilled decreases by -(1 - $''_T$) EV^T <0 if the tanker is actually monitored. The decrease in the expected volume of oil spilled due to actually monitoring a transfer operation is larger, the lower the probability of being monitored. From the agency's point of view, there is more to be gained from actually monitoring a tanker if the probability of being monitored is low $-(1-\alpha_{\mathrm{T}})EV_{\mathrm{T}}^{\mathrm{T}} > 0$. Thus the expected volume of oil spilled also decreases at a decreasing rate in absolute value with the private good effect of the probability of monitoring.

Effort spent on harbour patrols is the second type of measure available to the agency to reduce the volume of oil spilled. It is also a public good type measure, but a distinction has to be made between the public good effect of the probability of monitoring and the frequency of harbour patrols. Harbour patrols have a broader public good effect. Since they affect all types of ships in the harbour, we assume that increases in the frequency of harbour patrols increases the level of pollution prevention measures taken by the crew in charge of the vessel. It is assumed that the expected volume of oil spilled of both tankers and barges decreases at a decreasing rate in absolute value with harbour patrols, thus

$$V_H^{\mathrm{T}} = \frac{\partial EV^{\mathrm{T}}(P_{\mathrm{T}};f_H)}{\partial f_H} < 0, \qquad V_{HH}^{\mathrm{T}} = \frac{\partial^2 EV^{\mathrm{T}}(P_{\mathrm{T}};f_H)}{\partial f_H^2} > 0 \tag{3.7}$$

for the cases of tankers, and

$$V_H^{B} = \frac{\partial EV^{B}(P_{B};f_H)}{\partial f_H} < 0, \qquad V_{HH}^{B} = \frac{\partial^2 EV^{B}(P_{B};f_H)}{\partial f_H^2} > 0 \tag{3.8}$$

for the barges case (Appendix 1).

Oil spills may occur when a ship is moving in a harbour or during oil transfer operations. Equipment failures in the two cases are different, though there is some overlap. We assume the crew of a ship reacts to increases in the level of harbour patrols by increasing the level of care devoted to operations performed when the ship is moving in the harbour. If the probability of being monitored increases, the efforts are concentrated on the type of equipment and skills used during transfer operations. These differences lead to a trade off in the effectiveness of different types of monitoring. We assume that each enforced policy measure affects most intensively that type of pollution prevention equipment and skills used during the operations at which it is aimed; thus we assume:

$$\left| \frac{\partial^2 EV^{\mathrm{T}}(P_{\mathrm{T}};f_H)}{\partial P_{\mathrm{T}}^2} \right| > \left| \frac{\partial^2 EV^{\mathrm{T}}(P_{\mathrm{T}};f_H)}{\partial f_H \, \partial P_{\mathrm{T}}} \right| \tag{3.9}$$

and

$$\left| \frac{\partial^2 EV^{B}(P_{B};f_H)}{\partial P_{B}^2} \right| > \left| \frac{\partial^2 EV^{B}(P_{B};f_H)}{\partial f_H \, \partial P_{B}} \right|. \tag{3.10}$$

This does not imply that increases in the level of harbour patrols do not affect the effect of the probability of monitoring transfer operations; we allow for some cross effects. Consider the public good effect of the probability of monitoring transfer operations. In this case transfer operations, together with harbour patrols, can be thought as complementary inputs in the welfare (clean water) production process. Increasing one type of measure increases the marginal benefit that can be obtained from the other. Harbour patrols enhance the public good effect of monitoring transfer operations. For example, increases in the harbour patrol frequency increases the reduction of expected volume of oil spilled caused by monitoring transfer operations. The reduction in the expected volume of oil spilled due to increasing the probability of monitoring transfer operations increases with harbour patrols. Thus, it is assumed that

$$\frac{\partial EV^{\mathrm{T}}(P_{\mathrm{T}};f_H)}{\partial P_{\mathrm{T}}\,\partial f_H} < 0, \text{ and } \frac{\partial^2 EV^{B}(P_B;f_H)}{\partial P_B \partial f_H} < 0 \qquad (3.11)$$

for tankers and barges, respectively.

The higher the level of harbour patrols the less is to be gained from monitoring transfer operations. The higher the frequency of harbour patrols, the more is the care taken by ship owners and the fewer are the equipment failures left to be discovered during a transfer operation. The marginal benefit of actually monitoring a transfer operation $-(1-\alpha_{\mathrm{T}})EV_{\mathrm{T}} < 0,$ decreases with harbour patrols $-(1-\alpha_{\mathrm{T}})EV_H^{\mathrm{T}} > 0.$ An increase in the frequency of harbour patrols has opposite effects in the private and in the public good effects of monitoring transfer operations. We assume, however, that the overall effect of monitoring transfer operations increases with increases in the frequency of harbour patrols.

3.3 Effects of the Pollution Prevention Measures at the Harbour Level

The assumptions we made are in terms of an individual ship; now we look at the implications of these assumptions on the expected total volume of oil spilled in the harbour by all ships. Define $EW(m_{\mathrm{T}};m_B;f_H;\tau|n_{\mathrm{T}};n_B;\mathscr{E})$ to be expected volume of oil spilled in the harbour during a period (0,*J*] given: (i) n_I tankers and n_B barges transferring oil in the harbour during that period, (ii) m_I of the tankers' and m_B of the barges' transfer operations are monitored, (iii) f_H is the level of harbour patrolling, (iv) the long run level of enforcement effort is $\mathscr{E}$, and (v) let d_T represent the total number of tankers in the harbour, taking into account that m_I of them have been monitored, i.e., $d_T = (n_T-(1-\alpha_T)m_T) = (n_T-m_T)+\alpha_T m_T,$ the same for barges, d_B. Therefore, the expected volume of oil spilled in a harbour equals:

$$EW = (n_{\mathrm{T}} - m_{\mathrm{T}}(1-\alpha_{\mathrm{T}})P_{\mathrm{T}})\ EV^{\mathrm{T}}(P_{\mathrm{T}};f_H \mid \mathscr{E}) + (n_B - m_B(1-\alpha_B)P_B)\ EV^{B}(P_B;f_H \mid \mathscr{E})$$

Recall from (3.5) and (3.6) that the vessel expected spilled volume decreases at a decreasing rate with the private effect of monitoring a transfer operation. Also the vessel expected spilled volume decreases at a decreasing rate with the public good effect of the probability of monitoring. The public good effect of the probability of monitoring at the harbour level equals the sum of the public good effects on each of the tankers in the harbour. Therefore, the expected volume of oil spilled in a harbour decreases at a decreasing rate with monitoring oil transfer operations. That is,

$$EW_{\mathrm{T}} = -(1-\alpha_{\mathrm{T}})EV^{\mathrm{T}}(P_{\mathrm{T}},f_H) + d_{\mathrm{T}}/n_{\mathrm{T}}EV^{\mathrm{T}}_{\mathrm{T}}(P_{\mathrm{T}},f_H)<0 \text{ and,}$$

$$EW_{\mathrm{TT}} = -2(1-\alpha_{\mathrm{T}})EV^{\mathrm{T}}_{\mathrm{T}}(P_{\mathrm{T}},f_H) + d_{\mathrm{T}}/n_{\mathrm{T}}\,EV^{\mathrm{T}}_{\mathrm{TT}}(P_{\mathrm{T}},f_H) > 0.$$

Equivalently for the case of barges:

$$EW_B = -(1-\alpha_B)EV^{B}(P_B,f_H) + d_B/n_B EV^{B}_{B}(P_B,f_H) < 0, \text{ and}$$

$$EW_{BB} = 2(1-\alpha_B)EV^{B}_{B}(P_B,f_H) + d_B/n_B EV^{B}_{BB}(P_B,f_H) > 0.$$

In the case of harbour patrols the vessel expected spilled volume decreases at a decreasing rate in absolute value, therefore, the reduction on the volume of oil spilled in the harbour decreases with harbour patrols at a decreasing rate. Thus,

$$EW_H = EV^{\mathrm{T}}_{H}d_{\mathrm{T}} + EV^{B}_{H}d_B < 0,$$

$$EW_{HH} = EV^{\mathrm{T}}_{HH}d_{\mathrm{T}} + EV^{B}_{HH}d_B > 0.$$

From (3.11) it is implied that the overall effect of monitoring transfer operations increases with harbour patrols. Thus:

$$EW_{\mathrm{T}H} = -(1-\alpha_{\mathrm{T}})EV^{\mathrm{T}}_{H} + \frac{d_{\mathrm{T}}EV^{\mathrm{T}}_{\mathrm{T}H}}{n_{\mathrm{T}}} < 0.$$

in the tankers case. And for barges:

$$EW_{BH} = -(1-\alpha_B)EV_H^B + \frac{d_B EV_{BH}^B}{n_B} < 0.$$

We assume that $EW_{H\mathrm{T}} - EW_{HB} = 0$, that is the effect of harbour patrols on the marginal benefit of monitoring tankers and barges is the same.

3.4 Optimal Allocation of Enforcement Effort

The agency chooses the number of each type of ship to be monitored and the frequency of harbour patrols. We assume that there is no transfer operation that last longer than the period chosen to allocate effort. The agency's problem can be stated as choosing the number of tankers and barges to be monitored and the man-hours devoted to harbour patrols to minimize the volume of oil spilled during a period of time $(0,\tau]$ given the man power resources available. Thus, define $EW(m_{\mathrm{T}};m_B;f_H;\tau|n_{\mathrm{T}};n_B;\mathscr{E})$ to be the expected volume of oil spilled in the harbour during a period $(0,\tau]$ given: (i) n_t tankers and n_B barges transferring oil in the harbour during that period, (ii) m_t of the tankers' and m_B of the barges' transfer operations are monitored (iii) f_H is the level of harbour patrolling, and (iv) the long run level of enforcement effort is $\mathscr{E}$. Therefore, the expected volume of oil spilled in the harbour equals:

$$\min_{m_t, m_B, f_H} EW = (n_{\mathrm{T}} - m_{\mathrm{T}}(1-\alpha_{\mathrm{T}})P_{\mathrm{T}})EV^{\mathrm{T}}(P_{\mathrm{T}};f_H) + (n_B - m_B(1-\alpha_B)P_B)EV^B(P_B;f_H).$$

$$s.t.\ e(\tau) = h_{\mathrm{T}}m_{\mathrm{T}} + h_B m_B + f_H$$

$$P_{\mathrm{T}} = \frac{m_{\mathrm{T}}}{n_{\mathrm{T}}} \text{ and } P_B = \frac{m_B}{n_B}.$$

$$0 \le P_{\mathrm{T}} \le 1 \text{ and } 0 \le P_B \le 1$$

where: h_t, h_B are the number of hours spent by the agency in monitoring a tanker and a barge respectively and $e(J)$ is the number of hours available for enforcement effort.

Assuming an interior solution, the first order conditions require that the optimal number of tankers and barges monitored transfer operations (i.e. m_I, m_B) and man-hours allocated to harbour patrols f_H satisfy:

$$d_{\mathrm{T}}\frac{EV_{\mathrm{T}}^{\mathrm{T}}(P_{\mathrm{T}},f_H)}{h_{\mathrm{T}}n_{\mathrm{T}}} - (1-\alpha_{\mathrm{T}})\frac{EV^{\mathrm{T}}(P_{\mathrm{T}},f_H)}{h_{\mathrm{T}}} = d_B\frac{EV_B^B(P_B,f_H)}{h_B n_B} - (1-\alpha_B)\frac{EV_B(P_B,f_H)}{h_B} \tag{3.12}$$

$$d_{\mathrm{T}}\frac{EV_{\mathrm{T}}^{\mathrm{T}}(P_{\mathrm{T}},f_H)}{h_{\mathrm{T}}n_{\mathrm{T}}} - (1-\alpha_{\mathrm{T}})\frac{EV^{\mathrm{T}}(P_{\mathrm{T}},f_H)}{h_{\mathrm{T}}} = d_{\mathrm{T}}EV_H^T(P_{\mathrm{T}},f_H) + d_B EV^{B_H}(P_B,f_H). \tag{3.13}$$

$$h_{\mathrm{T}}m_{\mathrm{T}} + h_B m_B + f_H = e(\tau) \tag{3.14}$$

Condition (3.12) is the efficiency condition across monitoring transfer operations of different types of ships. Efficiency requires that the ratio between marginal social benefit and marginal cost of monitoring transfer operation be equal for all ship types. Condition (3.13) is the efficiency condition across monitoring transfer operations and harbour patrols. It is the classical public good efficiency condition where the marginal benefit of monitoring tankers transfer operations equals the marginal benefit of the public good, harbour patrols. Harbour patrols affect all ships in the harbour so the marginal benefit of harbour patrols is the sum of the marginal individual benefits, d_I tankers and d_B barges, in the harbour. Monitoring transfer operations only affects one type of ships, tankers in this case. Equivalently this condition could have been expressed in terms of the marginal benefit of barges. Notice that monitoring transfer operations is both a public and a private good, but it only affects a concrete type of ships, it is like a local public good. The public good effect of the probability of monitoring is represented by $d_{\mathrm{T}}EV_{\mathrm{T}}^{\mathrm{T}}/n_{\mathrm{T}}h_{\mathrm{T}}$. A unit increase in the number of tankers monitored m_I decreases the expected volume of oil spilled by $EV_{\mathrm{T}}^{\mathrm{T}}/n_{\mathrm{T}}$, and it affects the d_I tankers in the harbour. The larger the number of a type of ship in the harbour, the larger the public good effect of monitoring that type of ship. But in the case of monitoring transfer operations what causes the public good effect is the probability of being monitored, decreases as the number of tankers increases in the harbour. So in allocating effort to monitoring transfer operations the agency has to take into account that the larger the number of tankers in the harbour the more ships are affected by the policy but also the smaller the probability of being monitored. The private good effect is represented by $(1-\alpha_{\mathrm{T}})EV^{\mathrm{T}}(P_{\mathrm{T}},f_H)/h_{\mathrm{T}}$. It represents the amount by which the expected volume of oil spilled by tankers that have actually been monitored decreases. It completes the effect of monitoring transfer operations. Condition (3.14) is the agency budget constraint.

4 COMPARATIVE STATICS AND POLICY MEASURES

We may now list and discuss a number of comparative static results showing how optimal policy measures change when there is an increase in the number of tankers in the harbour.

$$\frac{\partial m_B}{\partial n_T} = \frac{1}{D}\left[-p_T EW_{TT}\, EW_{HH} + h_T \left(EV_H^T - P_T EV_{HT}^T \frac{d_T}{n_T}\right) \frac{EW_{TT}}{h_T^2}\right] < 0. \tag{4.1}$$

$$\frac{\partial m_T}{\partial n_T} = \frac{h_B}{D}\left[P_T \frac{EW_{TT}}{h_T}\left(EW_{HH} - 2\frac{EW_{HB}}{h_B} + \frac{EW_{BB}}{h_B^2}\right) + \left(EV_H^T - P_T\, EV_{HT}^T \frac{d_T}{n_T}\right) \frac{EW_{BB}}{h_B^2}\right]. \tag{4.2}$$

$$\frac{\partial f_H}{\partial n_T} = \left[-\frac{h_T h_B}{D}\right]\left[P_T \frac{EW_{TT}}{h_T}\frac{EW_{BB}}{h_B^2} + \left(EV_H^T - P_T EV_{HT}^T \frac{d_T}{n_T}\right)\left[\frac{EW_{TT}}{h_T^2} + \frac{EW_{BB}}{h_B^2}\right]\right]. \tag{4.3}$$

where:

$$D = h_T h_B EW_{HH}\left(\frac{EW_{TT}}{h_T^2} + \frac{EW_{BB}}{h_B^2}\right) - 2\left(\frac{EW_{TT}}{h_T} EW_{HB} + \frac{EW_{BB}}{h_B} EW_{HT}\right) + \frac{EW_{TT}}{h_T}\frac{EW_{BB}}{h_B} > 0. \tag{4.4}$$

If the number of tankers increases in the harbour, the marginal benefit of harbour patrols and marginal benefit of monitoring transfer operations increase. The marginal benefit of a public good is equal to the sum of the ship marginal benefits affected by the public good. There are more ships affected by harbour patrols so the marginal benefit of harbour patrols increases. As the number of tankers affected by monitoring tanker transfer operations increases so the marginal benefit of the probability of tanker monitoring increases.

The only policy measure by which marginal benefit is not affected is monitoring barges transfer operations, therefore to restore equality among the marginal benefits of each type of measure the marginal benefit of monitoring barges should increase. A decrease in the number of barges monitored increases the marginal benefits of this policy measure. So the optimal number of barges to be monitored decreases as the number of tankers increase in the harbour.

Increasing the number of tankers monitored decreases the marginal benefit of monitoring tankers. But the marginal benefits of harbour patrols increases. So the number of harbour patrols should be increased in order to decrease the marginal benefit of harbour patrols. But the total amount of enforcement effort remains constant, the resources that before were devoted to monitoring barges transfer operations have to be allocated, both to monitoring tankers transfer operations and harbour patrols. How these resources should be assessed depends on how marginal benefit of harbour patrols and the marginal benefit of monitoring tankers transfer operations increases with the number of tankers in the harbour n_I.

Proposition 1: If increases in the number of tankers in the harbour increases the marginal benefit of monitoring tanker transfer operations more than the marginal benefit of harbour patrols then $\partial m_T/\partial n_T > 0$. That is, a sufficient but not necessary condition for $\partial m_T/\partial n_T > 0$. is:

$$\left| P_T \frac{EW_{TT}}{h_T} \right| \geq \left| EV_H^T - P_T EV_{HT}^T \frac{d_T}{n_T} \right| \tag{4.5}$$

where:

$$\frac{\partial EW_T}{\partial n_T} = -P_T \frac{EW_{TT}}{h_T} < 0.$$

$$\frac{\partial EW_H}{\partial n_T} = EV_H^T - P_T EV_{HT}^T \frac{d_T}{n_T} < 0.$$

Proof: From equation (4.2)

$$\begin{aligned}\frac{\partial m_T}{\partial n_T} &= \frac{h_B}{D}\left[P_T \frac{EW_{TT}}{h_T}\left(EW_{HH} - 2\frac{EW_{HB}}{h_B} + \frac{EW_{BB}}{h_B^2}\right) + \left(EV_H^T - P_T\, EV_{HT}^T \frac{d_T}{n_T}\right) \frac{EW_{BB}}{h_B^2}\right] \\ &= \frac{h_B}{D}\left[P_T \frac{EW_{TT}}{h_T}\left(EW_{HH} - 2\frac{EW_{HB}}{h_B}\right) + \left(\frac{P_T EW_{TT}}{h_T} + \left(EV_H^T - P_T EV_{HT}^T \frac{d_T}{n_T}\right)\right) \frac{EW_{BB}}{h_B^2}\right]\end{aligned} \tag{4.6}$$

Then and given assumptions made above:

$$\frac{\partial m_T}{\partial n_T} > 0 \;\; if \left| P_T \frac{EW_{TT}}{h_T} \right| \geq \left| V_H^T - P_T EV_{HT}^T \frac{d_T}{n_T} \right|$$ Q.E.D.

Corollary 1: A necessary condition for $\frac{\partial m_T}{\partial n_T} < 0$ is:

$$\left| P_{\mathrm{T}} \frac{EW_{\mathrm{TT}}}{h_{\mathrm{T}}} \right| < \left| EV_{H}^{\mathrm{T}} - P_{\mathrm{T}} EV_{H\mathrm{T}}^{\mathrm{T}} \frac{d_{\mathrm{T}}}{n_{\mathrm{T}}} \right| \tag{4.7}$$

Proof: The first term of expression (3.6) is always positive so for $\frac{\partial m_{\mathrm{T}}}{\partial n_{\mathrm{T}}} < 0$ it is necessary but not sufficient that the above condition is satisfied.

Proposition 2: If the number of tankers increases in the harbour and the increase in the marginal benefit of monitoring tanker transfer operations is smaller than the increase in the marginal benefit of harbour patrols then $\partial f_H / \partial n_{\mathrm{T}} > 0$. That is, a sufficient but not necessary condition for $\partial f_H / \partial n_{\mathrm{T}} > 0$ is that condition (4.7) is satisfied (or 4.5 not satisfied).

Proof: From equation (4.3) we have:

$$\frac{\partial f_H}{\partial n_{\mathrm{T}}} = \left[-\frac{h_{\mathrm{T}} h_B}{D} \right] \left[P_{\mathrm{T}} \frac{EW_{\mathrm{TT}}}{h_{\mathrm{T}}} \frac{EW_{BB}}{h_B^2} + \left(EV_H^{\mathrm{T}} - P_{\mathrm{T}} EV_{H\mathrm{T}}^{\mathrm{T}} \frac{d_{\mathrm{T}}}{n_{\mathrm{T}}} \right) \left[\frac{EW_{\mathrm{TT}}}{h_{\mathrm{T}}^2} + \frac{EW_{BB}}{H_B^2} \right] \right].$$

$$\left[-\frac{h_{\mathrm{T}} h_B}{D} \right] \left[P_{\mathrm{T}} \frac{EW_{\mathrm{TT}}}{h_{\mathrm{T}}} \left(EV_H^{\mathrm{T}} - P_{\mathrm{T}} EV_{H\mathrm{T}}^{\mathrm{T}} \frac{d_{\mathrm{T}}}{n_{\mathrm{T}}} \right) + \left[\frac{EW_{\mathrm{T}}\mathrm{T}}{h_{\mathrm{T}}} + \left(EV_H^{\mathrm{T}} - p_{\mathrm{T}} EV_{H\mathrm{T}}^{\mathrm{T}} \frac{d_{\mathrm{T}}}{n_{\mathrm{T}}} \right) \right] \frac{EW_{BB}}{h_B^2} \right]. \tag{4.8}$$

Given the assumptions made above

$$\frac{\partial f_H}{\partial n_{\mathrm{T}}} > 0 \ \ if \left| P_{\mathrm{T}} \frac{EW_{\mathrm{TT}}}{h_{\mathrm{T}}} \right| < \left| EV_{H}^{\mathrm{T}} - P_{\mathrm{T}} EV_{H\mathrm{T}}^{\mathrm{T}} \frac{d_{\mathrm{T}}}{n_{\mathrm{T}}} \right| \qquad \text{Q.E.D.}$$

Corollary 2: A necessary but not sufficient condition for $\frac{\partial f_H}{\partial n_{\mathrm{T}}} < 0$ is:

$$\left| P_{\mathrm{T}} \frac{EW_{\mathrm{TT}}}{h_{\mathrm{T}}} \right| > \left| EV_{H}^{\mathrm{T}} - P_{\mathrm{T}} EV_{H\mathrm{T}}^{\mathrm{T}} \frac{d_{\mathrm{T}}}{n_{\mathrm{T}}} \right|$$

Proof: The first term of expression (4.8) is always positive so for $\frac{\partial f_H}{\partial n_{\mathrm{T}}} < 0$ it is necessary that the above condition is satisfied. Q.E.D.

If condition (4.5) is satisfied then the optimal policy rule is to increase the number of monitored tankers and decrease the number of monitored barges when the number of tankers increases in the harbour. Also condition (4.5) is necessary for $\partial f_H / \partial n_{\mathrm{T}} < 0$. Therefore, it is likely that if the marginal benefit of monitoring tanker transfer operations increases more than the marginal benefit of harbour patrols the number of harbour patrols should be reduced. Condition (4.5) is more likely to be satisfied the more sensitive the marginal expected volume of oil spilled is to monitoring transfer operations and the larger the rate at which the marginal volume of oil spilled decreases with an increase in monitoring transfer operations.

If condition (4.5) is not satisfied and the number of tankers increases in the harbour then the agency has to increase the number of harbour patrols. Thus, the optimal policy rule is to decrease the number of monitored barges and to increase the number of harbour patrols.

The difference between the increases in the marginal benefit of monitoring transfer operations and harbour patrols when the number of tankers increases in the harbour is an empirical result. Increases in the number of ships in a harbour decreases the probability of being monitored, so both, the marginal benefit of the private and public good effect of the probability of monitoring increases. Increases in the number of ships increases the marginal benefit of harbour patrols, the marginal benefit of harbour patrols depends also on the probability of being monitored. Decreases in the probability of monitoring has a negative effect on the marginal benefit of harbour patrols.

5 CONCLUSIONS

The stochastic model developed here allows us to see how each step of the spilling process is affected by each policy measure and to compare the relative efficiency of different measures in reducing spills. We show that efficiency requires that the marginal social benefit of monitoring a transfer operation be equal for all ship types. And also, it is necessary that the marginal benefit of monitoring transfer operations equal the marginal benefit of harbour patrols.

The comparative static results show that the optimal number of barges to be monitored decreases as the number of tankers increase in the harbour. The resources that were devoted to monitor barges transfer operations should be allocated, both to monitor tanker transfer operations and harbour patrols. How these resources should be assessed depends on how the marginal benefit of harbour patrols and the marginal benefit of monitoring tanker transfer operations increases with the number of tankers in the harbour. If increases in the number of tankers in the harbour increases the marginal benefit of monitoring tanker transfer operations more than the marginal benefit harbour patrols then the number of harbour patrols should be increased. Also if it is the marginal benefit of harbour patrols that is larger then the number of harbours patrols should be increased. Together with estimation of these parameters the model allow us to predict among other, the expected number of oil spills per ship during a transfer operation, and the expected volume of oil spilled.

This model can be used for other types of environmental issues where the arrival of pollution is stochastic in nature such as, in general, transportation or handling of hazardous wastes. Note that the model can be generalized to different types of processes. We can define a process not only by type of ship but also by other characteristics like type of operation that the ship was performing when the spill occurred, and cause of the spill. The more precise the description of a process the better it allows us to allocate effort to minimize a specific type of spill. For example, we assume that the damage function is a linear function of the model, it allows us to assume that minimizing the expected volume of oil spilled is equivalent to minimize social damage. But this assumption can be seen as a limitation of the model if damage increases at an increasing rate with spill size more effort should be allocated to avoid large spills. The model allows us to solve this limitation if we can associate a type of process to a spill size. We conclude saying that looking at pollution arrivals as a combination of stochastic process can allow the pollution prevention agency to allocate the pollution prevention measures to minimize the more harmful processes.

APPENDIX 1

RANDOM VOLUME OF OIL SPILLED

To assume that $V^{T}_{TH} < 0$ and $V^{B}_{BH} < 0$ for tankers and barges respectively, it implies that the less P_I is used in order to attain the same level of clean water the use of f_H has to increase at an increasing rate.

Let $-V^{\mathrm{T}}(P_{\mathrm{T}}, f_H)(1-(1-\alpha_{\mathrm{T}})P_{\mathrm{T}})$ the benefit (volume of clean water produced) attained with policy instrument P_I and f_H. Then the second order necessary conditions for concavity imply:

$$\left(V^{\mathrm{T}}_{\mathrm{TT}} - 2(1-\alpha_{\mathrm{T}})V^{\mathrm{T}}_{\mathrm{T}}\right)V^{\mathrm{T}}_{HH}d_{\mathrm{T}} - \left(V^{\mathrm{T}}_{\mathrm{T}H}\ d_{\mathrm{T}} + (1-\alpha_{\mathrm{T}})V^{\mathrm{T}}_{H}\right) > 0.$$

If $V^{T}_{H\mathrm{T}} < 0$ then

$$|V_{\mathrm{TT}}V_{HH}| > |\left(V_{H\mathrm{T}}d_{\mathrm{T}} + (1-\alpha_{\mathrm{T}})V^{\mathrm{T}}_{H}\right)^2|.$$

because

$$|V_{H\mathrm{T}^2}| > |\left(V_{H\mathrm{T}}d_{\mathrm{T}} + (1-\alpha_{\mathrm{T}})V^{\mathrm{T}}_{H}\right)^2|.$$

If $V_{H\mathrm{T}} < 0$ then for strict concavity we need:

$$|V^{\mathrm{T}}_{\mathrm{TT}}V^{\mathrm{T}}_{HH}d_{\mathrm{T}}| > |V^{\mathrm{T}}_{HH^2}d_{\mathrm{T}^2} + (1-\alpha_{\mathrm{T}})^2V^{\mathrm{T}^2}_{H}| \quad \text{and}$$

$$|V^{\mathrm{T}}_{HH}V^{\mathrm{T}}_{\mathrm{T}}| > |V^{\mathrm{T}}_{H\mathrm{T}}V^{\mathrm{T}}_{H}|$$

Notice that we need to make some assumptions about the first derivatives in this case in order to satisfy the second order necessary conditions.

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