Preface and Introduction

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At the Arctic and Marine Oil Spill Program Seminar (1995) it was reported that millions of tons of oil per year are entering the marine environment, half arising from marine transportation. Although tanker disasters have provided the most lasting images in the public mind of the horrible effects of oil pollution, spills of this kind produce an annual average of only 25% of the oil entering the sea through marine transportation activities. The other 75% results from thousands of discharges made each day by ships in the course of routine operations. The first goal of our project was to develop a theoretical framework broad enough to allow modelling of these oil spill phenomena without imposing differences in the approach between types of spill 'a priori'. We established models in which all types of spill are probabilistically subject to reductions through changes in legislation and enforcement. The underlying economic process is the maximization of expected profits by vessel owners or operators. 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 phenomenon is fundamentally stochastic in nature. More specifically, oil spills depend on a large number of factors: the year in which the ship was built, the skills of the crew, the level of maintenance of the equipment, the weather conditions, etc., many of which are under the control of the ship owner, but no one of them has had a deterministic relationship with the amount 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 capable of modifying the distribution of this series of events in the desired way.

The optimization problem of the pollution prevention agency

Suppose the goal of the pollution prevention agency (PPA), such as the Coast Guard, is to minimize the social damage caused by oil spills during a period of time. The social damage function is related to the damage function, which assigns a cost level to each spill. We take the social damage from all spills to be also the sum of the costs associated with each individual spill. Thus, minimizing the expected volume of oil spilled is equivalent to minimizing the social damage.

The agency can use several types of policy measure. At present, two main types of pollution control policy are used: technological standards and economic incentives. Taken technological standards as given, we focus here on economic incentives. 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 the polluter being detected. The agency uses two methods for detecting oil spills: first, it randomly monitors transfer operations and, second, it patrols harbours and other areas looking for oil spills. The probability of detection and the response of ship owners to these measures depend on the hours devoted to them. In this project we 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-term effect on the ship behaviour. The agency reallocates effort periodically around some long-term average. Ship owners do not know ex-ante the pollution control enforcement effort level for the period of their arrival in the harbour, hut they are assumed to know the long-term average level of total enforcement effort. They react to the overall long-term expected enforcement effort level.

Once a ship arrives in the harbour, the ship operator learns the number of ships in the harbour and the enforcement effort level during that period. We expect ship owners to increase the level of care if the frequency of harbour patrols and probability of monitoring during their stay in the harbour are larger than 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-term or immediate effects of the pollution-control policies.

The optimization problem is described in terms of the volume of oil spilled instead of frequency of oil spilled and spill size. The pollution-control policy instruments give incentives to decrease the expected volume of oil spilled, but what is not clear is the effect of these pollution-control instruments on the frequency and size of oil spilled. We assume that ship owners act so as to decrease the expected volume of oil spilled with increases in the level of enforcement effort. However, the volume spilled is equal to the number of spills times the average spill size. Thus there are no clear implications either for frequency or spill size.

The optimization problem is solved only for two types of ship: tankers and barges. There is no (modelling) loss of generality, the conclusions can be generalized to the case of *m* types of ship. This model does not imply that the PPA randomly chooses the ships to be monitored.

The PPA policy takes into account the differences between types of ship. The model permits classification of ships in different categories depending on their history of pollution prevention and safety violations. The model is based on a comprehensive technical analysis, included in this Special Issue.

Stochastic modelling of pollution accidents

The stochastic models developed allow 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 the marginal social benefit of monitoring a transfer operation to be equal for all ship types, and also that the marginal benefit of monitoring transfer operations equals the marginal benefit of harbour patrols.

The comparative static results yield some simple observations: they show that the optimal number of barges to be monitored decreases as the number of tankers in the harbour increases. The resources that are devoted to monitor barge-transfer operations should be allocated, both to monitor tanker-transfer operations and to harbour patrols. How these resources should be assessed depends on how the marginal benefit of harbour patrols and the marginal benefit of monitoring tanker-transfers operations increase with the number of tankers in the harbour. If an increase 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 the number of monitored tankers should be increased. Also, if it is the marginal benefit of harbour patrols that is larger, then the number of harbour patrols should be increased. Together with the empirical estimations of these parameters, the model allows us to predict, among other things, 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 issue whore arrival of pollution is stochastic in nature. Note that the model can be generalized to different types of process. We can define a process not only by type of ship but also by other characteristics, such as 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, so it permits 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 avoid this limitation if we can associate a type of process to a spill size. We conclude that looking at pollution arrivals as a combination of stochastic processes can allow the PPA to allocate prevention measures to minimize the more harmful process.

Empirical consideration

Our objective here is to develop a specification suitable for empirical investigations on selected Baltic and Black Sea harbours, one that allows us to estimate the parameters of the theoretical model developed. We focus on the effects of economic incentive measures on the frequency of oil spills, spill size, and volume of oil spilled. We estimate the relationships between the parameters that describe the oil spill generation process and the enforcement effort.

We also study the efficiency of short-run economic incentive-type measures. Specifically, we concentrate on the effectiveness of monitoring transfer operations. We ask how, with a given level of investment in pollution control equipment, the behaviour of vessel owners changes with different levels of enforcement effort. The PPA is responsible for enforcing the law, and can do this by several means: (i) monitoring transfer operations, (ii) patrolling harbours and seaways, (iii) conducting examinations of ship equipment to check for compliance with pollution prevention and navigational safety, and (iv) the assessment of a fine.

We look at the performance of two of these pollution control measures: monitoring of transfer operations and assessment of penalties.

Estimating the effect of policy measures on the spill generation process requires us to assume the operation of a specific functional form, relating enforcement effort and the parameters that define the process. These parameters are determined by the behaviour of the ship owner. There are two ways to proceed. Either we can choose a specific functional form for the ship owner objective function (i.e., the expected profits per volume of oil transferred) and derive the corresponding functional forms for the parameters of the oil spill generation process; or we can specify functional forms for the relationship between the parameters that define the oil spill generation process and the enforcement effort variables.

Here, we choose the second approach. The first option would require solving the problem of ship owner profit maximization. Instead, we choose a functional form that can represent the responses of profit-maximizing ship owners to changes in the enforcement effort level.

The traffic in a harbour is characterized by a vector of parameters showing the steady-state number of each type of ship in the harbour. We consider two types of ship, tankers and barges. The Coast Guard focuses its pollution prevention measures on these vessels. Other types of vessel generate oil spills, but they are not affected by the enforcement effort assigned to monitoring transfer operations, and we will therefore not consider them.

We assume that the steady-state number of ships in the harbour is independent of the level of pollution-control enforcement effort. Thus, we do not expect any strategic behaviour by ship owners trying to avoid harbours with a high level of enforcement effort. The characteristics of the oil spill generation process in each harbour depend, in part, on the composition of the fleet that operates in the harbour, that is, on the steady-state number of each type of ship. In harbours with a large proportion of oil-carrying vessels, we expect that spill size and volume of oil spills would be larger than in harbours where other types of ship are more frequent.

Assessment results and policy analysis

The results reported in this Special Issue emerged primarily from a RU-TACIS ACE project (T-94-1020-R) funded through the European Commission.

We experienced some difficulties in obtaining a consistent dataset for Russian harbours on the Baltic and Black Seas over the six years from 1990 to 1995. After many recalculations and continuous consistency checks, our TACIS ACE research group succeeded in generating a set of data that could be fitted to a simplified econometric model.

Datasets have several limitations. First, some ship characteristics, such as age, are not recorded, even for ships that spilled oil. Second, the characteristics of the ships in the harbour are recorded only for ships that spilled oil and were identified. Third, we do not have adequate data to estimate the relationship between the volume of oil spilled, the spill size, the number of oil spills during transit, and pollution control. The reason for this is that we do not have a precise measure of the effort that the harbour patrols actually allocate to enforcing pollution-control laws. Harbour patrols have several objectives other than detecting oil spills; for example, detecting and deterring the illegal movement of goods and persons. The proportion of effort allocated to each of these goals varies from harbour to harbour, but in general only the total number of hours allocated to harbour patrol is reported. Therefore, we cannot study the relationship between the number of oil spills during transit and harbour patrols.

Fourth, the area covered by the harbour patrols is not recorded, and so we also do not have a measure of the actual relevance of the hours allocated to harbour patrols. Fifth, we cannot empirically distinguish between the public and private good effect of the probability of monitoring. In order to distinguish between these two effects, we need to know the number of spills per ship, spill size, and volume of oil spilled for both non-monitored and monitored transfer operations, but the dataset does not include this information. Only the number of spills, the spill size and the volume that occurred in a harbour during a quarter and during a transfer operation are recorded. No distinction is made between monitored and non-monitored transfers.

Finally, and most important, we have data only on detected spills. Because increases in the enforcement effort will both increase the probability of detecting a spill and decrease the probability of oil being spilled, having data on detected spills makes it difficult to separate these two effects. If all spills caused were recorded, we could estimate the deterrence and detection effect of monitoring transfer operations, but it is difficult to record all the spills caused in the harbour. We suggest including in the pollution incidents dataset a variable that summarizes information about who reported the spill. It would be necessary to record only, whether the spill was reported by those who caused it, by the Coast Guard, or by a third party. Knowing the number of spills detected by each party, we could estimate the detection effect of monitoring transfer operations and estimate the deterrence effect more accurately.

In summary, the most important results of this analysis are: (i) the probability of a spill occurring decreases with increases in the probability of monitoring, (ii) the duration of the monitoring operation acts as an incentive to decrease the number of oil spills per transfer, (iii) the spill size does not depend on the level of enforcement effort, or on any of the other policies studied.

First, we showed that the probability of being monitored affects the probability of a spill occurring. Specifically, increases in the probability of being monitored reduces the probability of a spill occurring. This result is consistent for all harbours having high priority ships (HPS). Second, the duration of the monitoring operation also gives incentives to decrease the number of spills per transfer. We assumed that increases in the length of the monitoring operation have both a detection effect and a deterrent effect. The coefficient of the length of the monitoring operation was consistently negative, which indicates that the deterrence effect is stronger than the detection effect. Third, we also show that the proportion of spills which were fined does not affect the frequency of spills. This is due to the low level of the fines, which give no incentives to improve the vessel's pollution-control equipment.

Although we were able to show that policy measures affect the frequency of oil spills, we also show that the policy measures studied were almost irrelevant to the size of the spills. Increases in the probability of monitoring do not affect the expected size of a spill. It can be argued that the expected size is not the appropriate parameter to examine in order to estimate the effect of monitoring on spill size. However, a study of the effect of the probability of monitoring on the spill size distribution function shows that the monitoring effort affects the spill size distribution function only in some cases. Our results therefore suggest that monitoring transfer operations is not the best policy for reducing the size of spills. It seems likely that once a spill has occurred, its size depends on its causes, i.e. the physical characteristics of the ship and the ship's operating environment.

Another important result is the optimality of the allocation of monitoring effort between tankers and barges. We could not identify an optimal policy for minimizing the amount of oil spilled in a harbour because we have no data on some of the policy measures used to enforce pollution control; for example, we could not estimate the effect of harbour patrols. But we tested whether the allocation of monitoring effort between tankers and barges is optimal, assuming that there is a finite amount of monitoring effort to he allocated between tankers and barges. We test the hypotheses of equality of marginal benefit of effort allocated to transfer operation by tankers and barges. The conclusions vary across regions. In the Black Sea region we cannot reject the null hypothesis of equality of marginal benefit from the monitored tankers and barges, but in the Baltic Sea region it appears that too much effort is allocated to monitoring tankers.

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